RESIN SPOTTING IN MEDIUM DENSITY FIBREBOARD

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CONTENTS

SUMMARY

This project investigated the problem of resin spotting in Medium Density Fibreboard, (MDF). It tried to determine the cause and also ways to eliminate the problem preferably from the source.

The object was to identify the process conditions which lead to a buildup in the blowline/dryer tube, identify the source of material leading to resin spot downgrade in the panel and determine strategies to prevent the buildup of this material in the blowline or in the dryer tube.

The measurements taken included monitoring of buildup on the blowtube and dryer walls, analysis of the resin jet, comparing the penetration distance with predictions, and investigating the fibre flow inside the blowtube at the point of resin injection. Also the mixing mechanism of the resin and the fibre was varied and any change in the amount of resin spotting occurring was monitored. Finally, a simple modelling experiment was performed on a possible method of separating the resin spot material from the fibre stream from within the dryer.

From this investigation it appears that the cause of resin spots in MDF is from the buildup of resinous material that occurs in mainly the dryer. After a certain period of building up, this material will detach itself from the wall and cause a particularly bad period of resin spotting. This is supported by the fact that calculations done on the rate of resin spot production from dryer buildup match the actual resin spot production rate encountered.

The conditions that lead to heavy buildup is mainly based on the amount of resin being injected into the fibre stream, ie a high resin content product produces a larger amount of buildup than a low resin content product and hence more resin spotting in general. However it is possible that there are other unidentified factors that also have an affect on resin spotting.

From our study of the resin mixing mechanism and the experiments that were carried out it is evident that the resin mixing mechanism has no affect on the amount of resin spotting. It was also noted that the unsteady flow of fibre appears to have no affect on resin spotting (from work done at other plants).

There appears to be no direct simple production strategy that could easily be implemented to prevent the buildup in the dryer of resin spot material other than what is been done at present (namely the china man's

hat on the dryer end of the blowtube and the weekly steaming and cleaning of the dryer).

It is the author's opinion that at present the best strategy for reducing resin spotting significantly in Medium Density Fibreboard is to employ a separator to remove the resin spot material from the fibre stream after the dryer. Separators have already been designed and are in use in other plants around the world and seem to have proved successful there. To this end it is recommended that the design of the existing dropout box could be improved to facilitate the separation of the resin spot material from the fibre stream.

CHAPTER 1. INTRODUCTION

1.1 General :

Medium Density Fibreboard (MDF) has achieved wide success as a premium product in the reconstituted wood panel market place. Much of this success has been in areas where the fine structure and strength of MDF has enabled it to be used as an alternative to solid wood. Unlike wood, where the inherent variability provides the visual and textural appearance of grain, MDF is manufactured with the aim of providing a product as uniform as possible so that the response of the material to machining and finishing operations is uniform and predictable.

MDF is a resin bonded wood fibre composite. In producing these wood panels, wood chips are reduced to fibres and then reformed into panels, the fibres being bonded together by additives such as synthetic resins.

In the case of medium density fibreboard, a member of the reconstituted wood panel family, not only are low quality wood resources able to be used, but a very high quality board is produced. MDF panels show high structural stability and much uniformity, both within and between panels.

1.2 Plant Description :

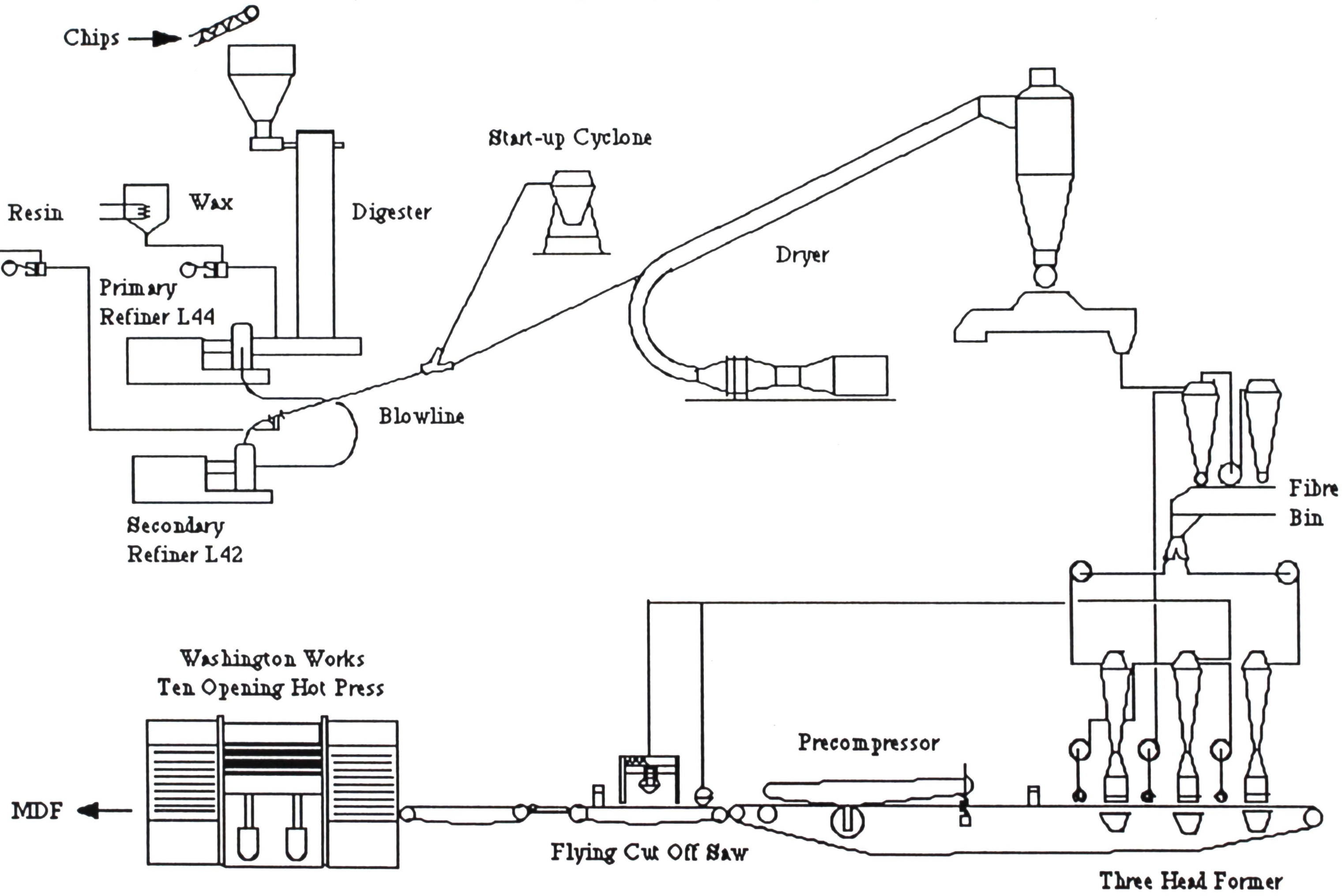
The Canterbury Timber Products (CTP) plant was commissioned in 1976 and has a nominal capacity of 100 tons per day. The plant is currently operating considerably in excess of this rate, over twice in fact, supplying urea-formaldehyde (UF) and melamine-urea-formaldehyde (MUF) bonded MDF panels to the local New Zealand market as well as to export markets.

I shall describe the process carried out at the Canterbury Timber Products plant, which is where this study was carried out, (see figure 1.1).

The wood, mostly in the form of small diameter logs, is debarked and chipped and then washed in water. The wood chips of approximately 80% softwoods,pinus radiata, and 20% hardwoods, a mixture which includes Douglas Fir, Corsican Pine, Ponderosa, Willow and Poplar, are subject to thermo-mechanical pulping (TMP) to produce the fibre-board raw material. This pulping method involves "cooking"

Fig 1.1
Simplified Plant Flow Diagram of CTP

(Modified from Chapman (1979) and Haylock (1977)



the wood chips in steam under high pressure in a vertical vessel, known as a digester, and then feeding the chips through a refiner which consists of two narrow slotted plates, one of which is rotating and the other is stationary. This creates extensive size reduction by shredding and also defiberation caused by sudden decompression. The fibreboard material is mixed with a small amount of wax (approximately 0.8% by weight of the fibres), which provides some water resistance to the boards, and synthetic resin (approximately 10% by weight of the fibres), which acts as a binder for the fibres. The resin is injected into the blowline (the small diameter pipe in which the fibres are transported about the plant at high velocity) and the turbulence mixes the fibre and resin together. The fibre-resin mix is then quickly flash dried in a tube dryer. Flash drying dries the fibres but is thought not to cure the resin. Note that the resin is mixed with the fibre before the fibre is dried. This contrasts with particleboard manufacture which involves drying the fibre first, and then adding the resin. The resin is thought to form a thin layer over the fibre surface by either being coated with a very fine spray of resin or by being smeared with larger drops of resin and then fibre to fibre contact spreading the resin over all the fibres. In reality a combination of both is probably responsible (ref Robson 1991).

At CTP the chips are first fed into a storage hopper above the vertical digester in which they are steam preheated, the steam being directly fed into the hopper through steam injection pipes. The steam condenses in the chips and heats the chips nearly to boiling point before they enter the digester. The chips are then fed through an infeed chute into a plug feed screw. The conical-shaped plug feed screw compresses the chips in the throat section leading to the digester vessel. The throat piece has seep holes allowing the water being squeezed out during the chip compression to escape. The chips are compressed into a plug, forming a seal between the pressure inside the digester housing and the atmospheric pressure at the infeed chute.

The digester vessel is pressurized with saturated steam to a pressure of about 120 psi. A blowback damper, pneumatically activated, rides on the plug of chips and helps break up the chips as they exit the throat piece. It also acts as as emergency seal between the digester and plug feed screw in case the plug should be lost.

The digester vessel has a volume sufficient for a retention time of about 5 minutes during normal operation. An adjustable chip level sensor automatically controls the fill level in the digester and thereby the retention time, by varying the speed of the plug feed screw bringing the chips into the digester. The residence time and hence the colour of the finished board is controlled by the height of the chips in the digester. In the digester, the chips are heated and softened suitable for refining. The digester vessel is cone-shaped, becoming wider at the bottom, to ensure the free outfeed of chips from the digester with the refiner feed screw.

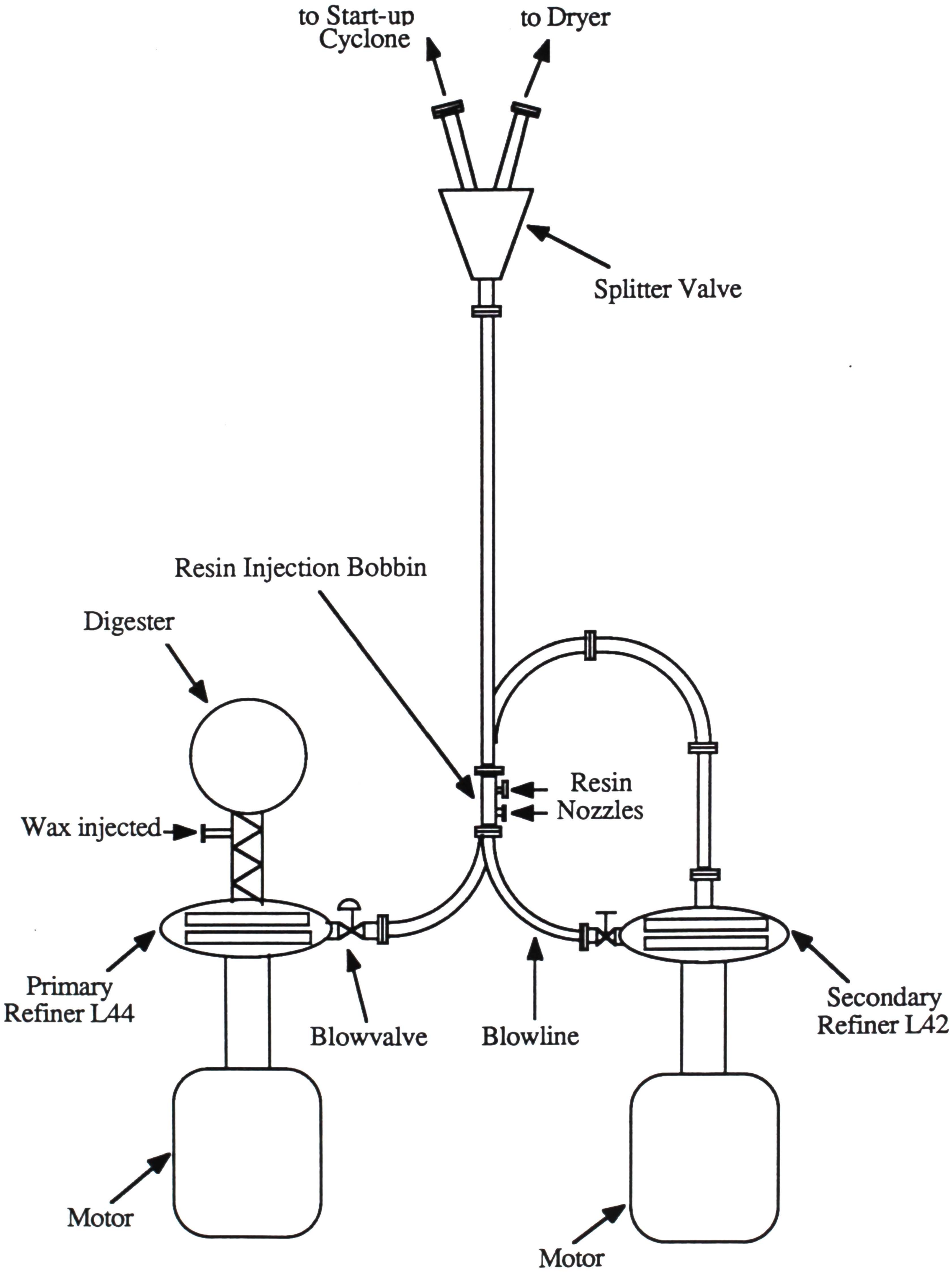
To ensure proper filling of the refiner feed screw, an agitator paddle rotates at the bottom of the digester. The refiner feed screw is a metering device and its speed determines the production rate of the refiner. The feed screw carries the chips through the centre opening of the stationary refining disc into the centre of the rotating disc. The chips enter the "refining" zone between the stationary and rotary disc and are shredded into fibre bundles. The gap between the stationary and rotating refiner plate is set manually. After leaving the refining zone, the fibre which is still pressurized enters the refiner housing.

The fibre leaves the refiner housing through the blow valve and enters the blowline which takes the fibre through a secondary refiner to the dryer passing through a diverter valve. For start-up and shut down, this diverter valve can direct the fibre into a start-up cyclone for disposal.

CTP currently is operating with two refiners in series, (see Fig 1.2), the raw material being screw fed into the first refiner, a Defibrator L44, and out the control blow valve to the second refiner, a smaller L42 Defibrator. Liquid paraffin wax is injected into the screw between the digester and the primary refiner. The resin is added in the blowline after the secondary refiner and ahead of the flash tube dryer. From the dryer, the fibre is collected in a cyclone and after passing through a small 'dropout' box, is transferred to a fibre storage bin, (the 'dropout' box is designed to collect any large heavy lumps in the fibre stream). The fibre storage bin contains sufficient fibre only for about 3-4 minutes of forming line operation. From the fibre storage bin, the fibre is transferred, through another two 'dropout' boxes, to the first and third forming heads on the forming line where it is laid to form the mat. The second forming head lays down fibre from the scalpers of the first and third forming heads and from the mat edge trim saws. The fibre mattress is continuously formed and is moved down the production

Fig 1.2
Refiners and Resin Injection Arrangement

(plan view)



line where it first passes through a precompressor before being cut into lengths by a circular flying cut-off saw. These slabs of fibre are loaded into a Washington Iron Works ten platten 5700 tonne hot press.The hot press uses two hot metal plattens on either side of each fibre mattress that are heated to about 200^{o}C by hot oil. These plattens compress the fibre by hydraulic forces, with normal compressive stresses up to about 25 MPa. The high temperatures in the press and also the acidity of the wood fibres result in the curing of the resin.

All the waste products produced through the manufacturing process such as bark from the log debarker, fines from the chipper, sawdust from cut to size saws and sander dust is burnt in a boiler providing steam for the refining process as well as heat for the press and dryer.

1.3 Blowline Blending of Resin and Fibre :

Blowline blending is defined as the addition of resin to the fibre moving along the blowline. This occurs between the fiberizing apparatus, in CTP's case two Defibrator pressurized refiners, and the dryer. This technique has been a standard practice in the production of dry process hardboard using phenolic resin as a binder.

When MDF production was started in the mid-sixties, fibre was first dried and then mixed with resin, usually in blenders of the same type as are commonly used in particleboard plants. Blowline blending was not used, probably because it was assumed that the resin would cure to some extent if it had to pass through the dryer with the fibre.

The first MDF plants used drum dryers, like Heil or Buttner dryers, in which the drying time was comparatively long. With the introduction of today's tube dryers, the drying time has been reduced to only a few seconds, which has reduced the risk of partial resin cure. Furthermore, since the fibre temperature is kept rather low during the drying - close to the wet bulb temperature, normally in the neighbourhood of 50^{o}C - it seemed feasible to utilize blowline blending in the production of urea formaldehyde resin bonded fibreboard.

Trials of blowline blending were carried out at CTP during November and December 1976 and it has been permanently used for all production since January 1977.

1.4 Resin Spotting in General :

MDF is a product which has a very fine, uniform structure, and when this product is made from mainly virgin Radiata pine has a light brown colour. Any dark spots are noticeable and if more than a specified size, approximately 3 mm in diameter, lead to downgrading of the panel. These spots arise from contamination of the fibre by bark, water (wet fibre), oil and resin. In general bark, water and oil spots arise from conditions and sources which are understood and for which control strategies are established. However resin spotting causes the largest proportion of downgrade due to spotting and has proved the most difficult to control.

The resin spots do not affect the board properties in any way but there is considerable customer resistance to non-uniform boards and hence boards with resin spots are downgraded and are used for other markets such as laminating and for moulded products.

1.5 Previous Work :

There is no detailed published work on this particular problem of resin spotting in MDF using blowline blending. There are however a number of published articles on related subjects, in particular on blowline blending itself, (see Bucking 1982, Gran 1982, Hammock 1982, Maxwell et. al. 1984) most of which occur in the Washington State University Symposium series.

Earlier work done at CTP noted that an inspection of both the blowline and the dryer show surface buildup which can break away and be carried through into the panel. The pattern of buildup was observed to be irregular and no specific conditions which influence it had been identified.

However the resin spot material had been analysed by nitrogen content, an indication of resin content (ref Snell & Hilton, 1967), and found to be 2-5 times higher in resin content than the average of the resinated fibre. The material that builds up on the dryer wall has also been analysed and found to be similarly higher in resin content.

1.6 Aim of this Project :

This project investigated the problem of resin spotting in Medium Density Fibreboard. It tried to determine the cause and also ways of eliminating the problem preferably from the source.

The object was to identify the process conditions which lead to a buildup in the blowline/dryer tube, identify the source of material leading to resin spot downgrade in the panel and determine strategies to prevent the buildup of this material in the blowline or in the dryer tube.

1.7 Hypotheses :

On initial analysis of the problem several hypotheses were formulated and subsequently investigated. They were as follows :

1. That the buildup on the blow-tube wall causes the resin spots to occur.
2. That the buildup on the dryer wall causes resin spotting.
3. That the unsteady flow of fibre and/or resin affects resin spotting.
4. That the resin mixing mechanism with the fibre has an affect on resin spotting.

CHAPTER 2. EXPERIMENTAL

2.1 System Description :

2.1.1 Blowline Details :

The blowline is the pipe in which the fibres are carried about the plant between the two refiners and to the dryer. It is constructed of, initially, approximately 100 mm square ducting changing to 100 mm inside diameter circular pipe just before the resin injection breach. Nozzle placement for the blowline resin addition is directly after a 90^{o} elbow, of about 0.9 metres radius, and on the inside bend of the pipe, (see fig 1.2).

The speed at which the fibre travels through the blowline is very rapid, approximately 100 m/s and it depends on the refiner housing steam pressure and the size of blow valve opening. The temperature in the blowline is about $150^{o}C$ and is at 480 kPa, (70 PSI). The volume of fibre is only about 0.2% of the volume of steam in the blowline and the volume of resin is about 10-20% of the fibre volume (ref Gran 1982). At CTP the mass ratio of fibre to steam was estimated to be 1:1.3 and the resin to fibre mass ratio is approximately 0.1:1. These figures will depend on the type of board that is being produced.

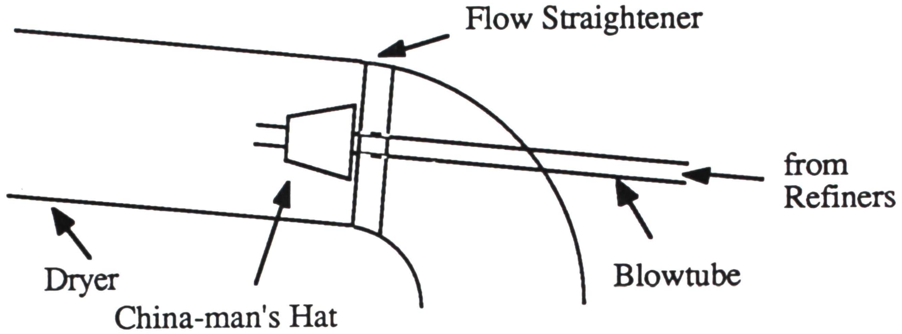
On the end of the blowline, inside the dryer, at CTP is a "china-man's" hat, (see fig 2.1), which is designed to alter the air flow to keep the wet fibre from contacting the dryers walls for as long as possible, by increasing the velocity of the air next to the jet of fibres and steam coming out of the blowtube and so reducing the angle of spread of the jet. The "china-man's" hat would also protect the jet from secondary flows generated around the bend in the dryer that were not removed, or reduced, by the flow straightener just before it.

2.1.2 Dryer Details :

The dryer is a flash tube type of dryer with a diameter of approximately 1.5 metre, (see fig 2.2). The air velocity in the dryer is about 24 m/s. The dryer inlet temperature is about $200^{o}C$ and the exit temperature is around $70^{o}C$ which gives a fibre moisture content of about 12% dry basis out of the dryer, for a moisture content of approximately 115% in the material entering from the blowtube.

Fig.2.1 CHINA-MAN'S HAT ON BLOWTUBE IN DRYER

a. General Arrangement



b. Detailed Specifications

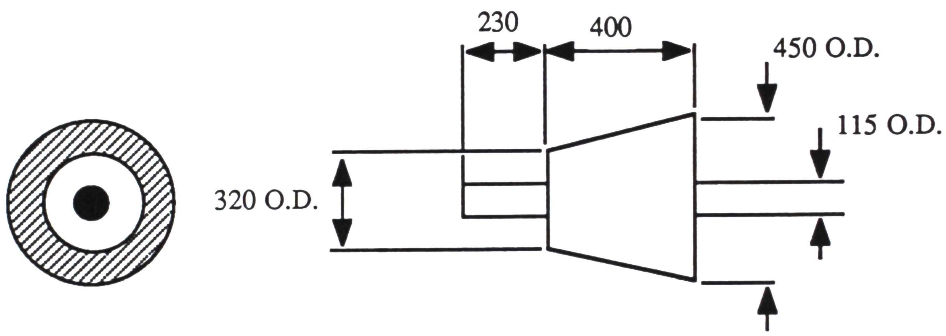
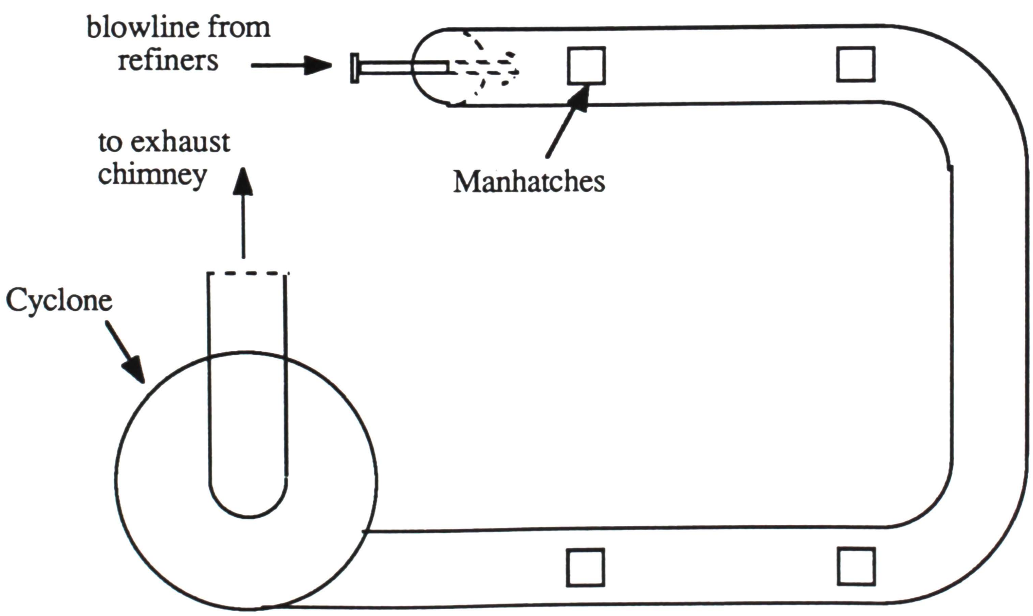


Fig 2.2 Dryer General Arrangement

(plan view)



2.1.3 Resin Nozzle and Pumping System :

The resin nozzle through which the resin flows into the blowtube is a simple circular straight through nozzle with a cleaning probe built in to enable it to be cleaned if it becomes blocked, (see figs 2.3 & 2.4). Originally it was of 7.0 mm diameter but this was later reduced to 5.5 mm to allow the resin to penetrate the blowtube further by increasing the velocity of the resin jet. The original system had two nozzles to allow for periodic cleaning with no disruption to the process. Also, if a high flow rate of resin was required it was necessary to use both of the nozzles otherwise the pressure in the line became too much and the pump pressure relief valves, set at 760 kPa (110 PSI), would trip open.

The resin is pumped from large outside storage tanks into smaller, 2500 litre, mixing tanks and then by two reciprocating pumps operating in parallel to the resin injection nozzles. CTP uses three different types of resin, they being a UF resin and a MUF resin from ICI and another UF resin from A.C. Hatrick. The resin storage tanks at CTP include two 135000 litre tanks for ICI UF resin, four 25000 litre tanks for ICI MUF resin and a 50000 litre tank for A.C. Hatrick UF resin. The resin pumps are two Milroyal variable stroke, with a capacity of 23.3 l/min (308 gph) each, powered by a single 4 kW (5.5 hp) motor. The resin flowrate is controlled automatically by a ratio controller from the digester feed screw rate.

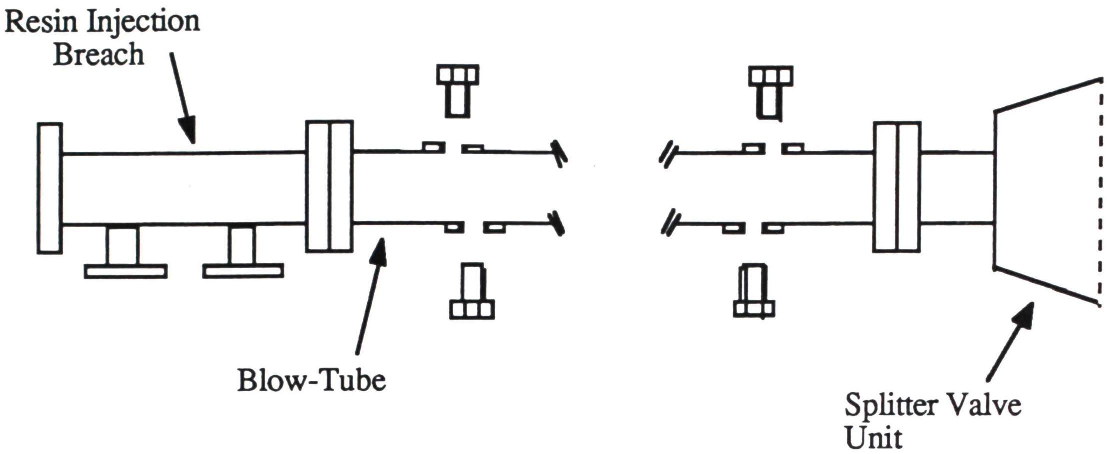
2.1.4 General :

The plant is normally shut down for maintenance once a week for a period of at least 4 hours, sometimes more depending on the work that is required to be done. During this time the dryer is first steamed and then cleaned out and any other maintenance that is required is carried out.

2.2 Experiments :

1. Tappings were put in the blowtube, (see fig 2.5) which consisted simply of 20 mm holes drilled in the pipe with nuts welded to the outside so that bolts could be used to seal them. The holes were offset so that the blowtube wall opposite could be inspected. The build-up on the blow-tube wall, both what was on the bolts and also the wall opposite each port, was monitored from time to time (not necessarily each shut).

FIG 2.5 BLOW-TUBE INSPECTION PORTS



2. A new injection breach with glass windows top and bottom was constructed, (see fig 2.6) to allow for analysis of the resin jet and the general fibre distribution. The viewing area of the windows was 30 mm wide by 160 mm long. It was then possible to take photographs of the resin jet and fibre flow and also analyse the fibre flow in the blowtube by measuring the response of a photodiode to light shone across the blowtube.

The photographs were taken using a Nikon FE2 camera with a Nikon 55 mm lens and a handheld remote flash; the film used was Ilford HP5. In some cases two flashes in rapid succession, of a known time delay, were used to attempt to determine the velocity of the fibres in the blowtube. The flash unit used was a Triple Head Flash unit that had been constructed in the department by university technicians and uses a Strobotron flash lamp, model 1538 P1, manufactured by GenRad of Massachusetts, U.S.A. The bulb has an energy rating of 0.5 J and a flash duration of 3 micro seconds.

The experiments using a photodiode were performed with a small 'AA' size 'Maglite' torch and the photodiode mounted on a "G" clamp, which fitted around the resin injection breach. The torch was modified to run off two 1.5 volt 'D' size batteries to give a longer life. The photodiode was a silicon photodiode made by R.S. Components, U.K., and was model number BPW21. It has a window diameter of 5.9 mm and was inserted in the far end of a 8 mm inside diameter tube that was 10 cm long. This was done so that scattered light would not reach the photo sensor.The photodiode response was amplified and analysed using a "Macquisition" data logger linked to a Macintosh Plus computer.

3. Inspection and monitoring of the dryer build-up was carried out. The build-up on the dryer wall was inspected after each shut, once a week, for a month and the amount of build-up noted. This was then attempted to be related to process conditions for the previous week since the last shut.

The next set of five experiments, (see 4 - 8 below), were all designed to test whether the mixing mechanism of the resin with the fibre has any affect on the amount of resin spotting. In general they were run for a period of two weeks to determine if there was any change.

During the running of the experiments the following was monitored : the type and amounts of board being produced, the resin content of these boards, the amount of downgrade due to resin spotting and also any changes in other board properties (such as board Internal Bond (I.B.), Modulus of Rupture (MOR), and Modulus of Elasticity (MOE), these are regularly monitored as part of the plant's quality control) was noted. An inspection of the dryer build-up during the weekly maintenance shut was also carried out.

4. A new vertical resin nozzle position was used for a two week period. This changed the position of resin injection, (see fig 2.7) and injected the resin into an area that is on average less concentrated in fibre, therefore giving the resin jet more time to break up into smaller drops before contacting the bulk of the fibre.

5. The resin injection breach was rotated 180^{o} for a two week period. This was designed to inject the resin into the bulk of the fibre that is in the far half (ie. outside bend) of the blowtube and will provide a different mixing pattern.

6. A smaller diameter nozzle was installed in the resin jets. This allowed the resin to penetrate further into the blowtube and injected the resin at a higher velocity.

Fig 2.3 RESIN SPRAY ASSEMBLY

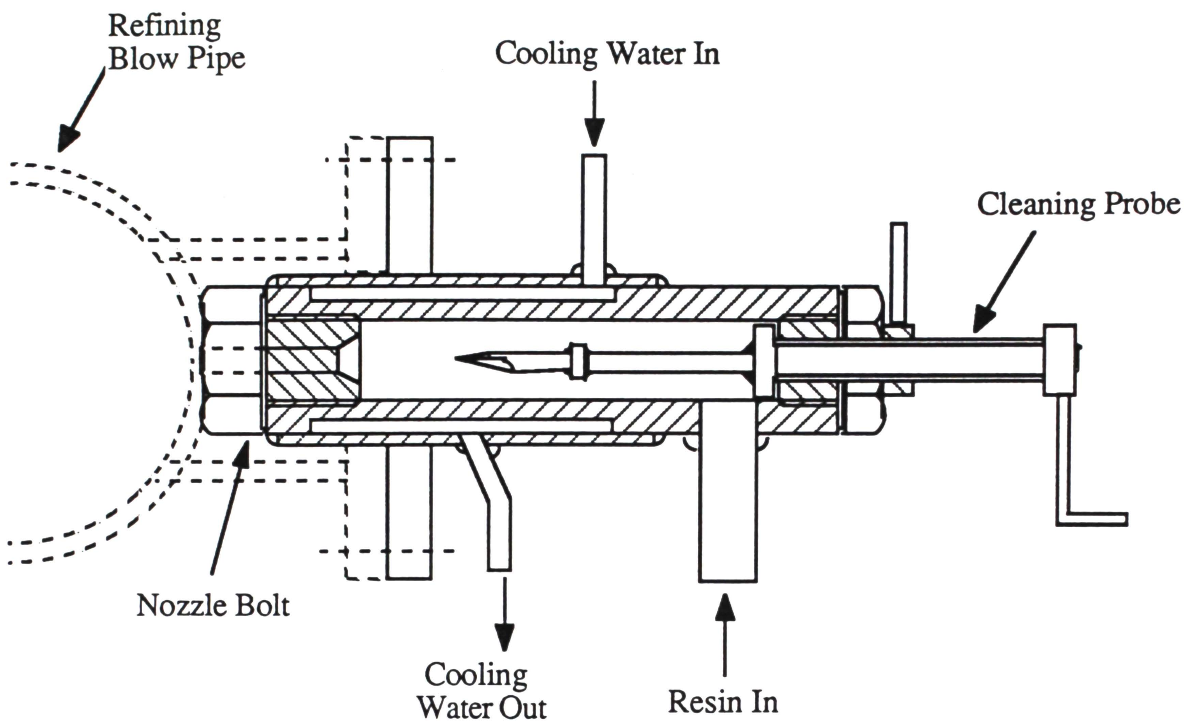


Fig 2.4 Nozzle Bolt - Detail

(All Dimensions in MM unless stated)

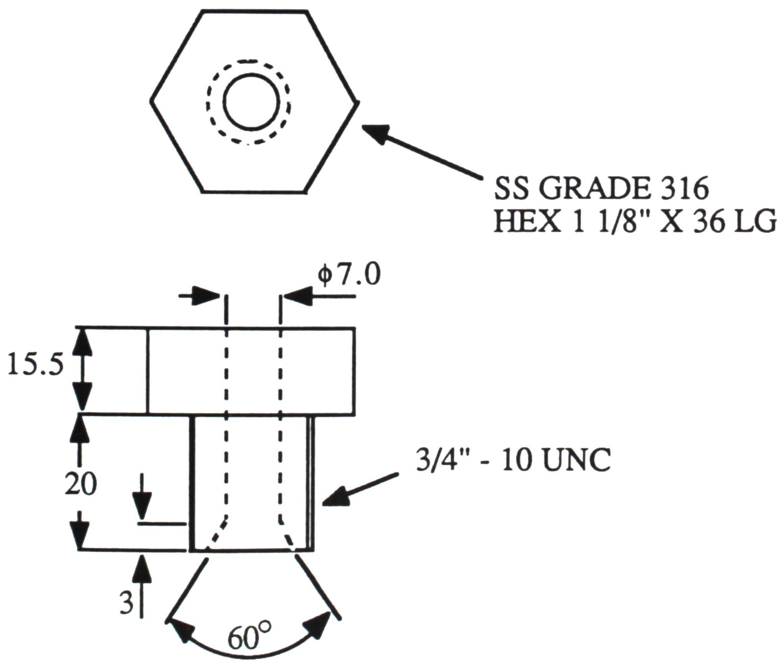
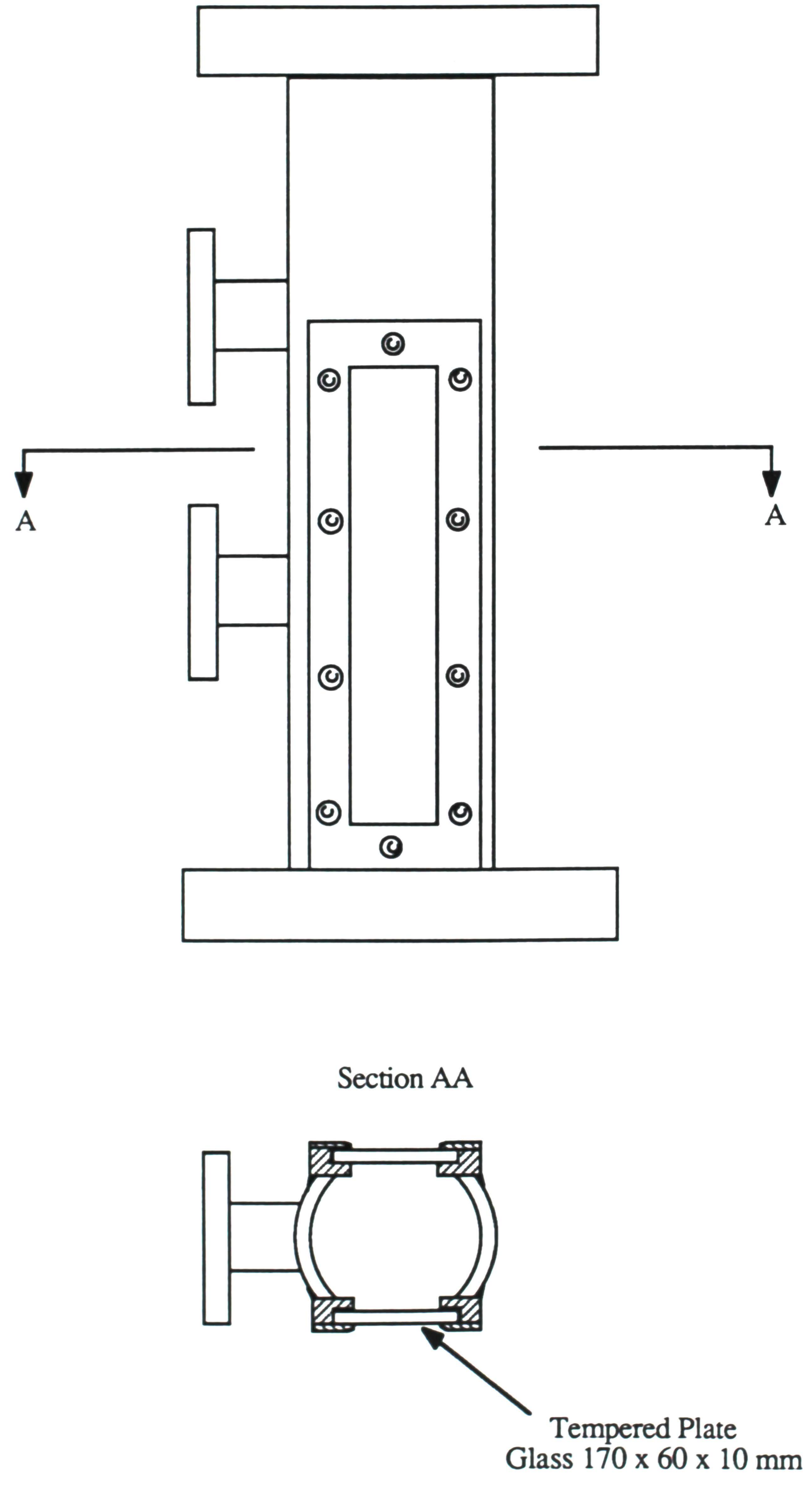


Fig 2.6 Diagram of Resin Injection Unit with Window



7. The resin was injected through three nozzles, using the original two injection ports as well as the added vertical resin injection port, (see fig 2.7). This was designed to spread the resin more evenly around the blowtube and provide a more even mixing mechanism.

8. Steam heating of the resin for short periods initially (2 hours approx) and later a longer trial of 8 hours. This was designed to reduce the viscosity of the resin to allow for an easier and quicker breakup of the resin jet. This was done through the existing nozzle. The calculated mean droplet size is significantly smaller than with the 'cold' resin (45 microns at 20°C as opposed to 270 microns at 70°C -see Appendix A) and should mean that there is less chance that a bundle of fibre will become soaked with resin and hence less resin spotting should occur. This is in line with the theory proposed by Dr David Robson (ref Robson 1991). The resin was heated by direct steam injection into the resin in a tube heat exchanger to 60°C, (see fig 2.8). This temperature was chosen as indications from literature (ref Pizzi vol 1.) suggested that the resin might degrade very rapidly at temperatures above this.

9. Separation experiments were carried out at the university to confirm whether a proposed separation technique for removing resin spot material from the fibre stream within the dryer was feasible. The idea that was developed was to use the dryer itself as a collector. Since heavier particles will tend to migrate to the bottom of the dryer tube, it seemed plausible that it should be possible to provide a trap in which to collect this material. Therefore a collection system placed just prior to the cyclone inlet should trap the resin spot material. An air curtain will be required to ensure that significant quantities of 'good' fibre is not collected.

Laboratory experiments were performed to test the practicalities of this collection mechanism. The experiments involved the basic modelling of the proposed system (see fig 2.9). The material taken off the dryer wall, (taken as similar to the resin spot material) was introduced into a 100 mm I.D. pipe by placing it inside the flow straightener and blocking the inner core while the fan and air curtain were started. Subsequently the material was released into the general flow. The amounts of material injected and collected were measured and collection efficiencies were computed.

Fig 2.7 New Resin Injection Port Position

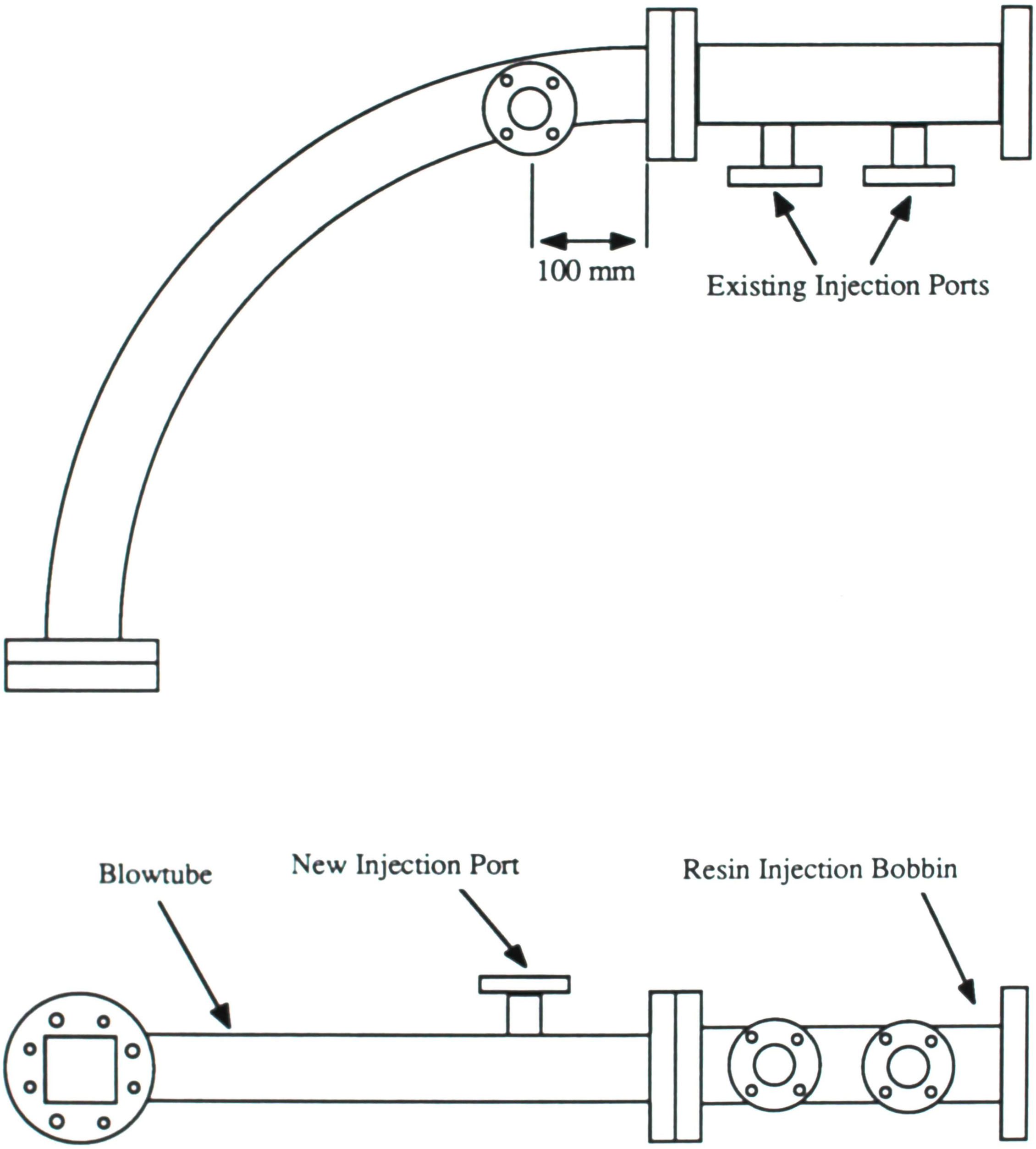


Fig 2.8 DIRECT MIXING RESIN HEATER

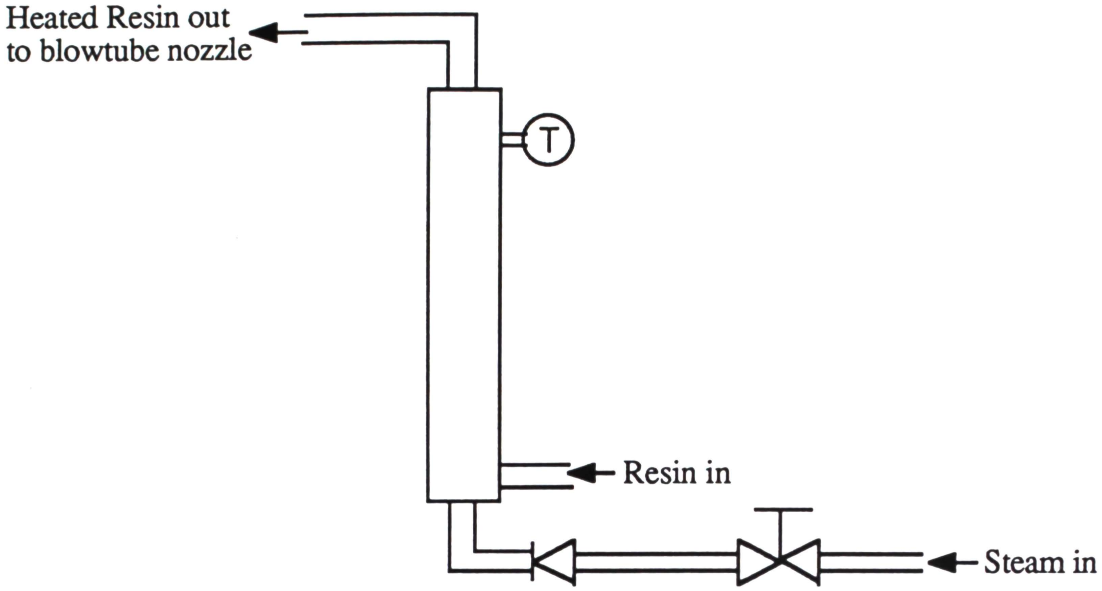
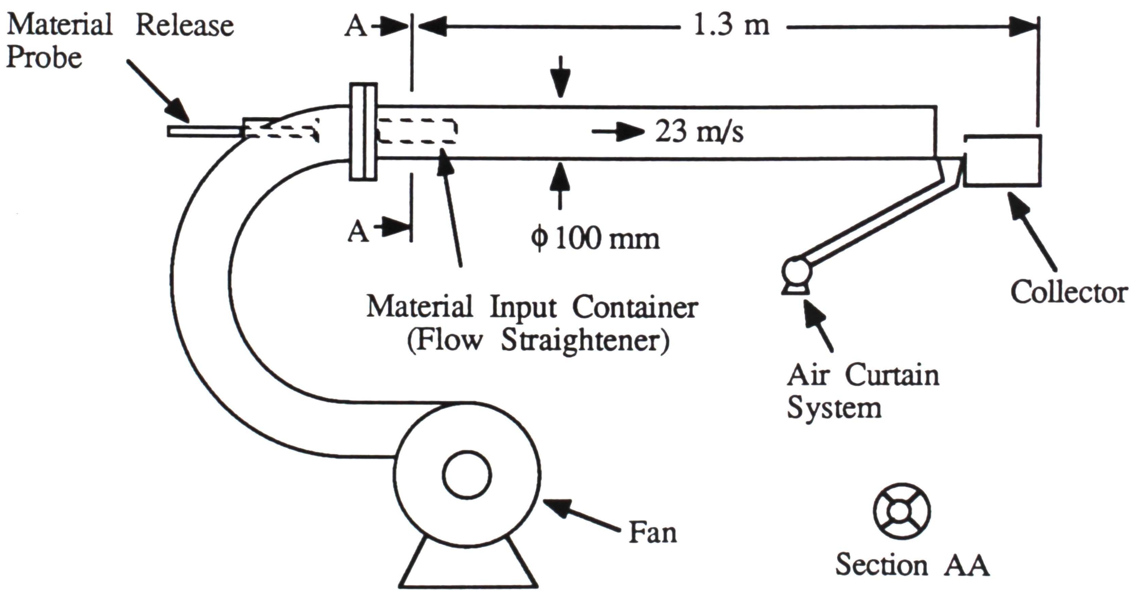


Fig 2.9
Resin Spot Material Separation
Experimental Arrangement



CHAPTER 3. RESULTS

3.1 The Buildup on the Blowtube Wall :

The buildup on the blowtube wall has been monitored by inspecting the bolts, that had been inserted in the blowtube wall, from time to time (not necessarily each shut). This was done after the blowline had been steam cleaned. (The dryer and blowline were steamed cleaned at the start of each maintenance shut, although towards the end of this project only the dryer was steamed cleaned as the steam lines had been altered). What was found was that there was a buildup on the bolts in general which was thicker on the bolts closer to the dryer than the bolts closer to the resin injection nozzles. This buildup appeared to be reasonably well stuck to the blowtube wall and took a bit of effort to scrape off, also it tended to stay behind in the blowtube when the bolts were removed. Inspection of the inside of the blowtube revealed that apart from immediately around the bolts the wall was relatively clean especially close to the resin injection nozzles.

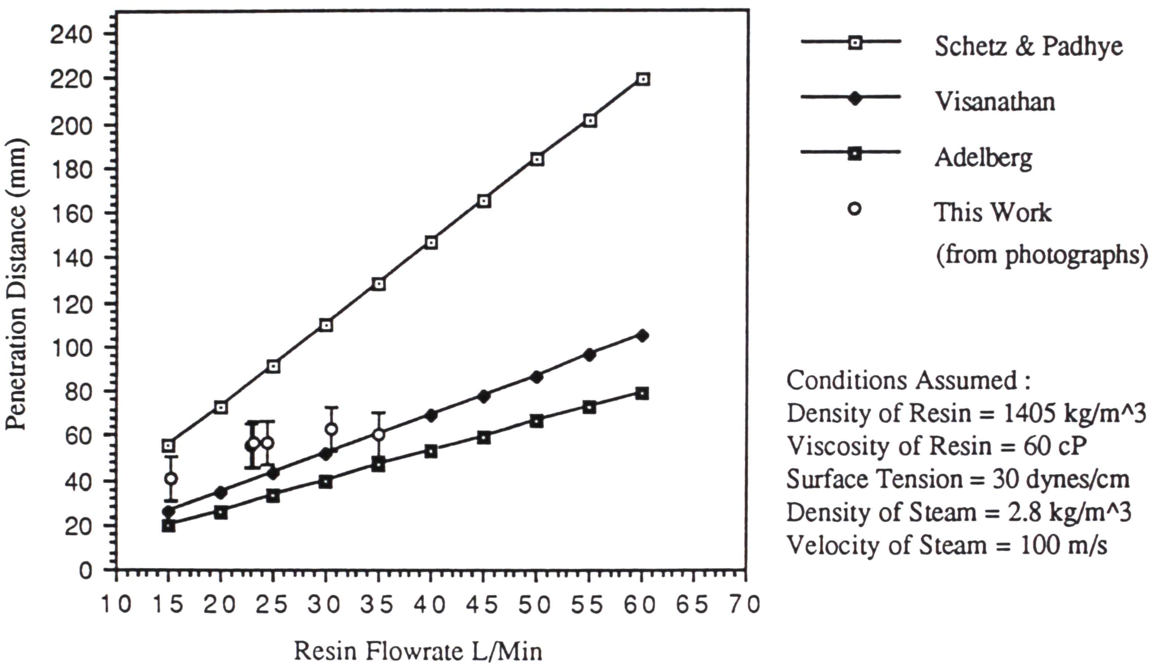
3.2 The Buildup on the Dryer Wall :

The buildup on the entire dryer wall was inspected after each shut for a month and the amount of buildup noted. In general the inspection was done after the dryer had been steamed cleaned, but prior to the dryer being completely cleaned out. This was found to vary only slightly from week to week for the time inspected. However a longer random inspection over a period of about twelve months resulted in significant variation in buildup being noted. Sometimes there was a lot of very flakey buildup up to about 2 mm thick which would start at different positions along the dryer and at other times there was very little buildup at all. The estimate of the average amount of buildup is up to 2 mm thick over about a 4 metre section of the dryer, (about 19 m^2 of area). No attempt was made to relate observations of dryer wall buildup with resin spotting.

3.3 Resin Jet Analysis :

From the photographs taken of the resin jet (see photographs in Appendix D) it has been possible to determine the mean penetration distance of the jet and hence compare with literature values calculated for the conditions we had. The jet was observed to change with varying resin flow-rate depending on the type of board being produced and also the production rate. As can be seen from the graph (see fig 3.1) of Predicted versus Actual Resin Penetration there is good general agreement between the experimental results and the theoretical predictions. (For theoretical predictions see Appendix A1 and refs Schetz and Padhye, Visanathan and Adelberg).

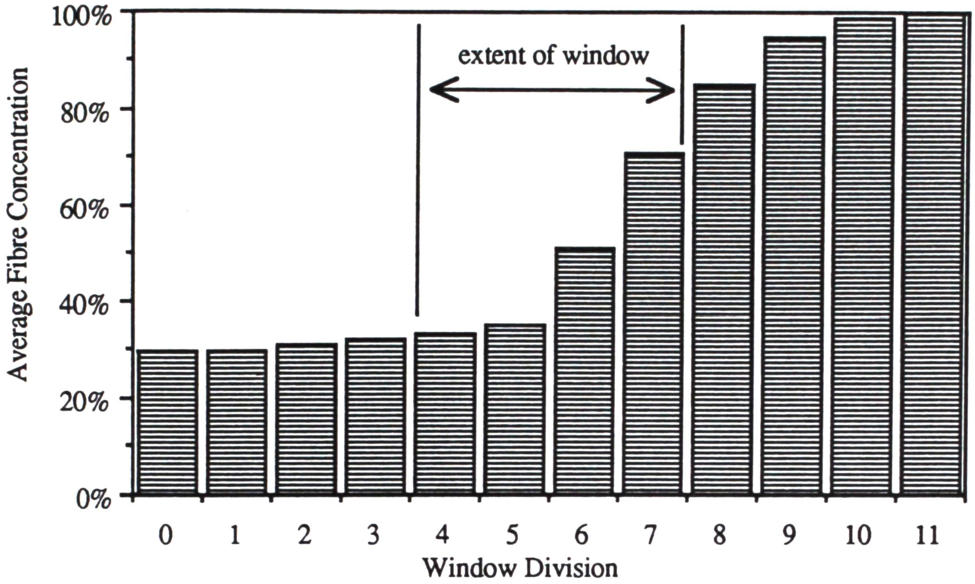
Fig 3.1 RESIN PENETRATION (PREDICTED VS ACTUAL)



3.4 Fibre Distribution in the Blowtube :

The fibre distribution in the blowtube has been analysed from the photographs that have been taken and a graph obtained (see fig 3.2 and Appendix A3) of the concentration of fibre across the window in the horizontal plane.

Fig 3.2
Fibre Distribution Across Blowtube
(Note that Divisions outside window are extrapolated)



3.5 Photodiode Analysis of Fibre Flow in the Blowtube :

The results from the photodiode analysis (see figs 3.3 a-d) showed that the flow in the blowtube is not steady and is pulsing at relatively low frequencies. Whether this is due to an unsteady fibre flow or due to the presence of water droplets in the blowtube is not known. Figure 3.3 a &b is of the plant running under normal conditions, and figure 3.3 c & d is of only steam flowing in the blowtube just prior to start-up. From figure 3.3 c it is apparent that there is some variation with just steam flowing which could be attributed to either a true variation in steam flow or due to the presence of water droplets in the steam. (The graphs shown are only 2 typical runs of numerous taken).

Conditions : Date = 16/10/90
Production Rate = 13.8 m3/hr
Secondary Refiner Housing Pressure = 580 kPa (84 PSI)
Steam Flow = 1.48 kg/s
Fibre Flow to Refiners (115% wet) = 5.4 kg/s

Fig 3.3a Photodiode Voltage Response - Run #1 (with fibre)

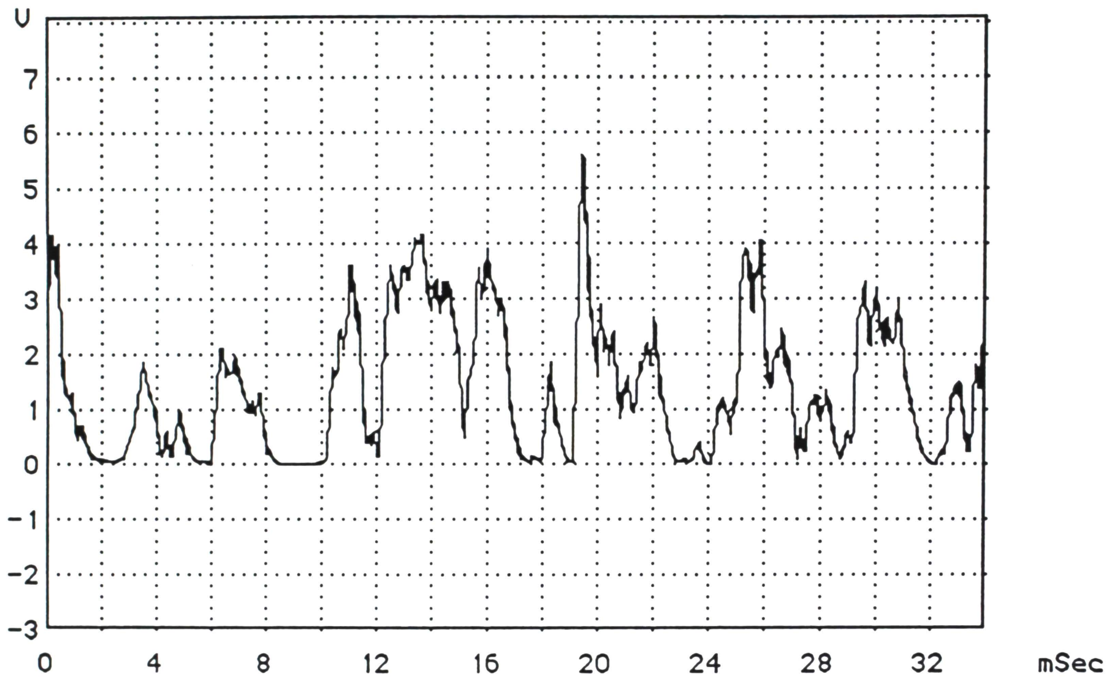
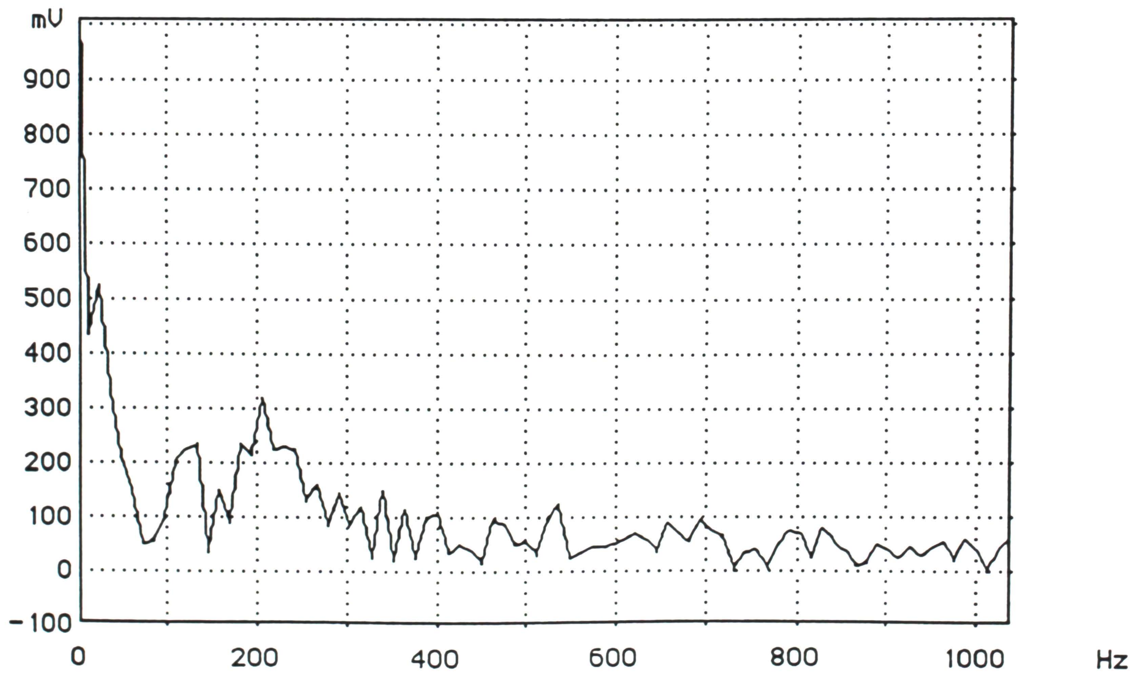


Fig 3.3b Frequency Response - Run #1



Conditions: Date = 8/11/90
Production Rate = 0 m^3/hr
Secondary Refiner Housing Pressure = 560 kPA (81 PSI)
Steam Flow = 1.5 kg/s
Fibre Flow to Refiners (115% wet) = 0 kg/s

Fig 3.3c Photodiode Voltage Response - Run #2 (no fibre flow)

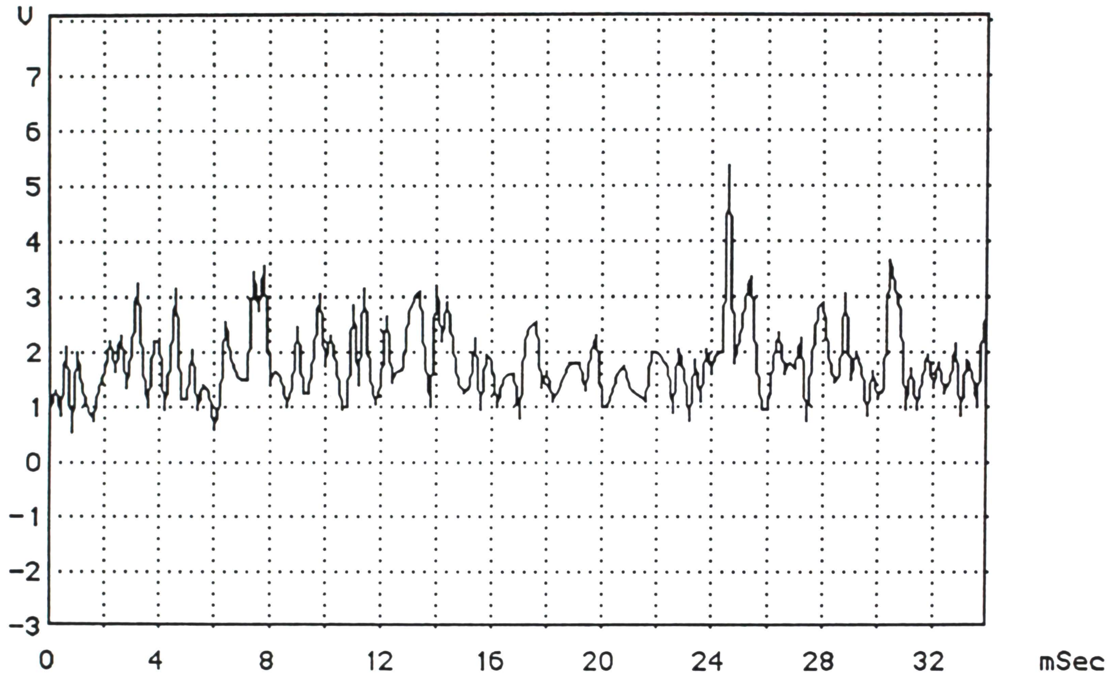
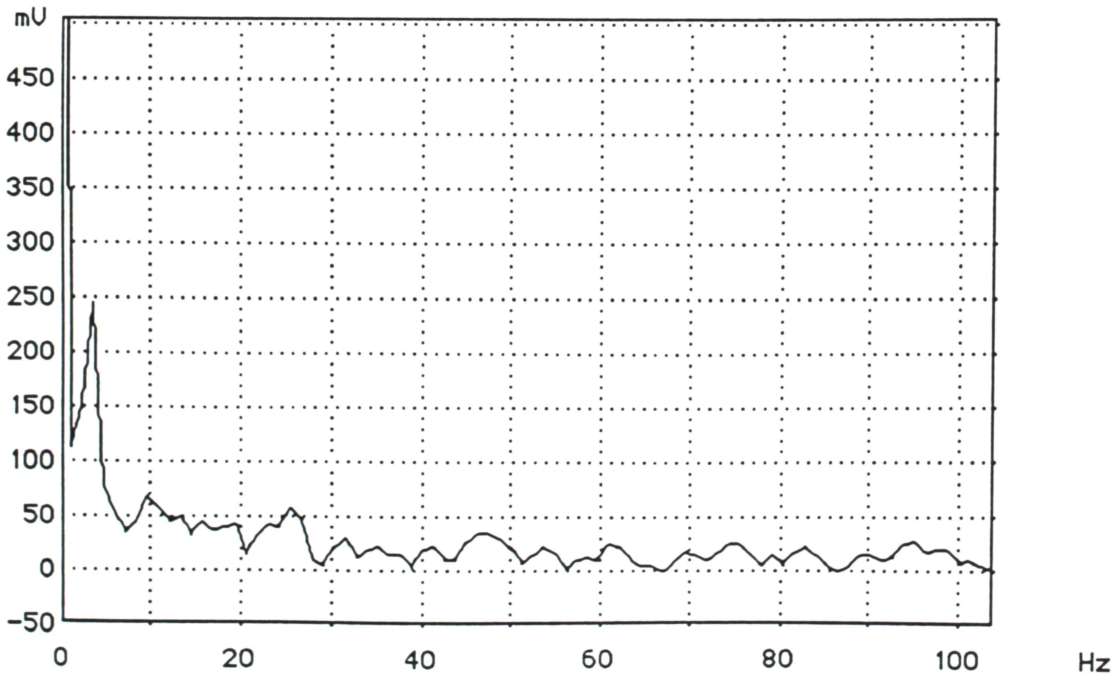


Fig 3.3d Frequency Response - Run #2



3.6 Velocity Measurements in the Blowtube :

The velocity measurements of fibre in the blowtube obtained from the photographs using a double flash gave velocities in the range of 78 to 103 metres per second, (see Appendix A9). This compares well with the expected values of 100 metres per second, which is that used and given in references, (ref Gran), and also calculated for the steam flow in the blowtube.

3.7 General Resin Spotting :

An investigation of plant records produced the graph of resin spotting (fig 3.4) on a month by month basis, averaged over each month, for the period of February 1987 till October 1991, (Plant computer based records started only in February 1987 hence this date was the earliest).

Graphs of the amount of regrade due to resin spotting were produced from 1990-91 plant data for Resin Content and also Board Thickness, (see figs 3.5 &3.6). This data was obtained by calculating the total amount of regrade due to resin spotting for the various board thicknesses and resin contents over the period of January 1990 to June 1991. This was done to determine if either of these two factors had a influence on resin spotting. A statistical analysis, see Appendix A5, of the significance of the slope of the graphs showed that the resin content did have an affect on resin spotting but board thickness did not.

Fig 3.4 Resin Spot Regrade
Feb-87 - Oct-91

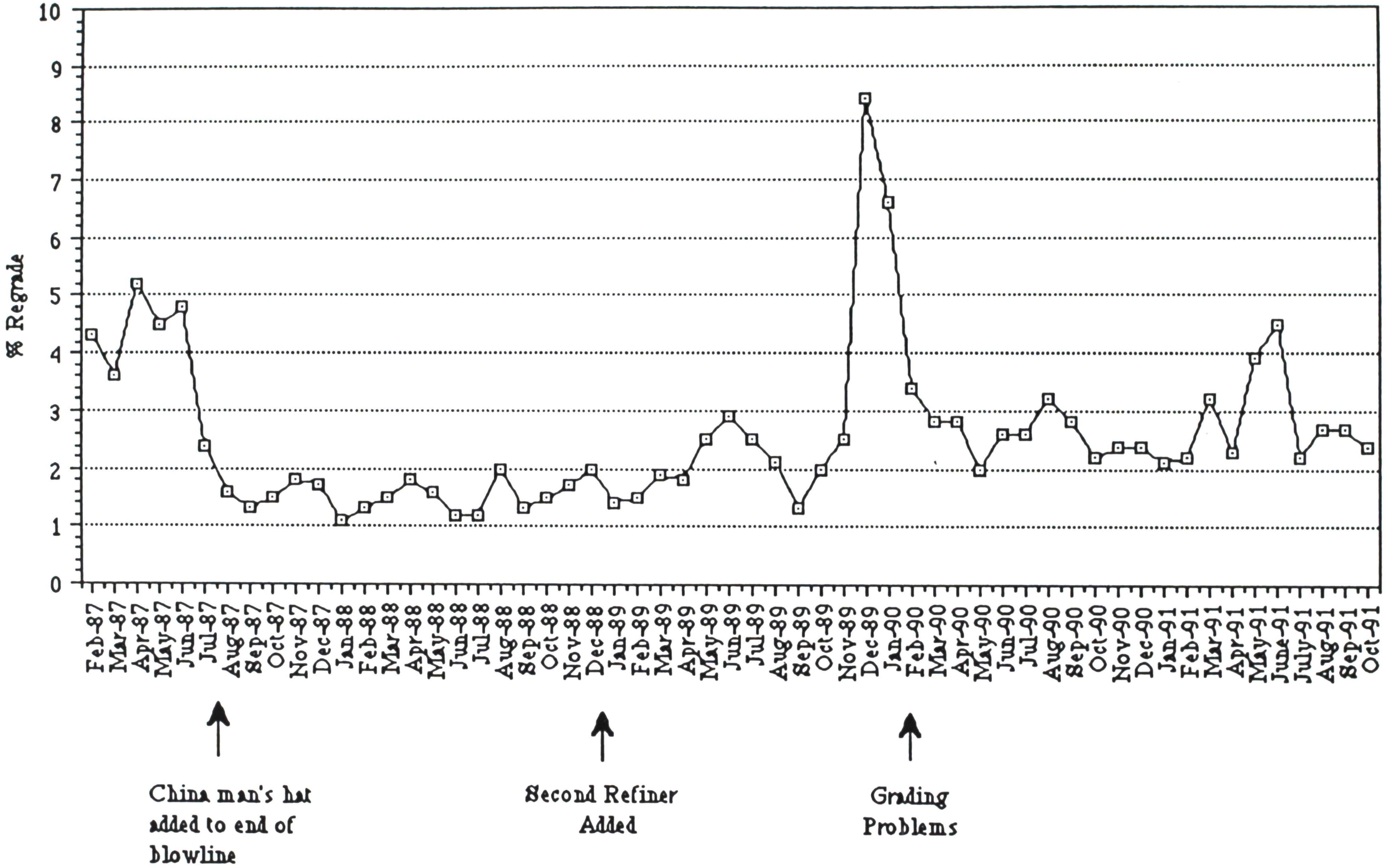


Fig 3.5 Regrade vs Resin Content

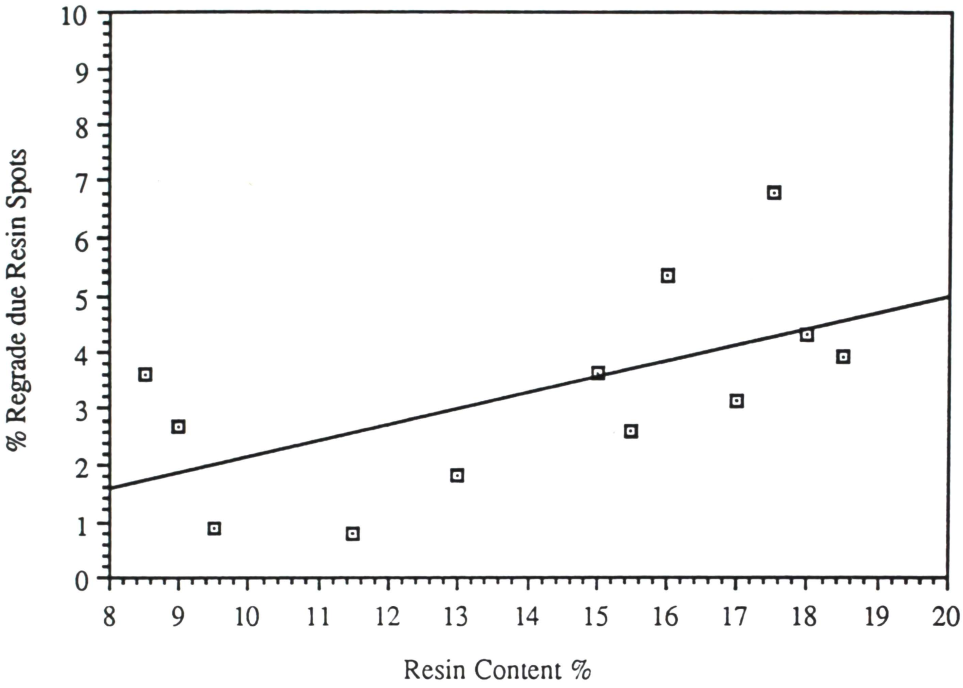
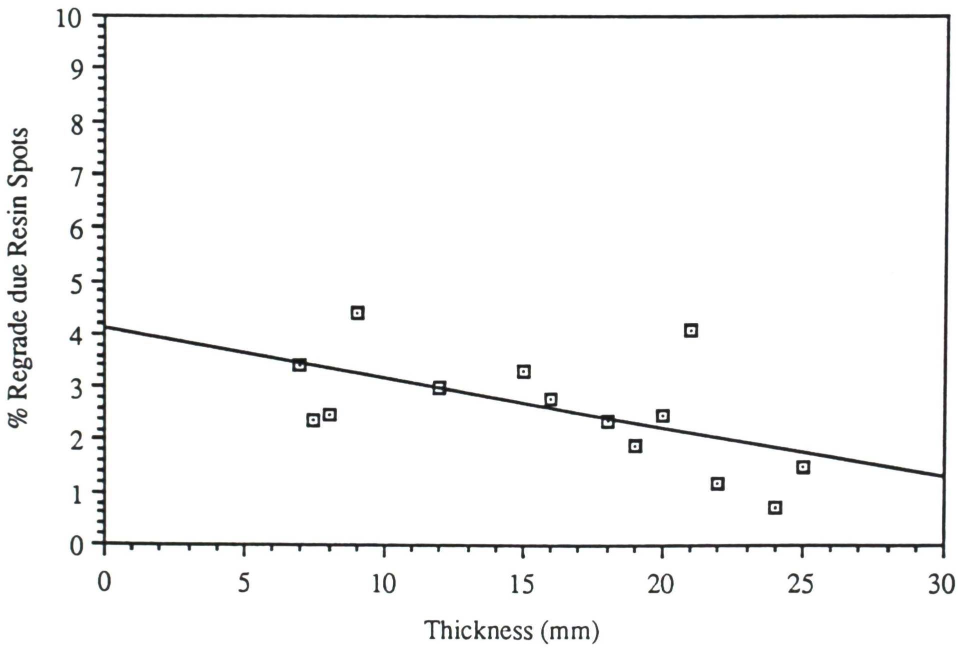


Fig 3.6 Regrade vs Board Thickness



3.8 Mixing Mechanism Experimental Results :

3.8.1 Vertical Nozzle Trial :

A new resin nozzle position was tried for a period of two weeks, from 21/3/91 to the 4/4/91, with no significant improvement, based on daily averages, in the amount of resin spotting that was occurring. The percentage of regrade due to resin spots remained about the same at an average 2.9%, (see fig 3.7a and b) and this has been approximately the average over the last six months or so (see fig 3.4).

Fig 3.7a Resin Spot Regrade
for March & April 1991 (weekly average)

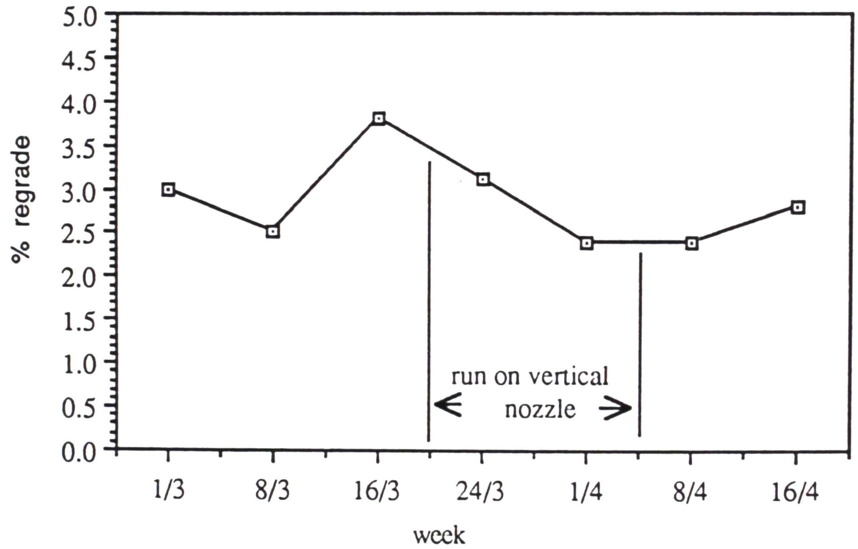
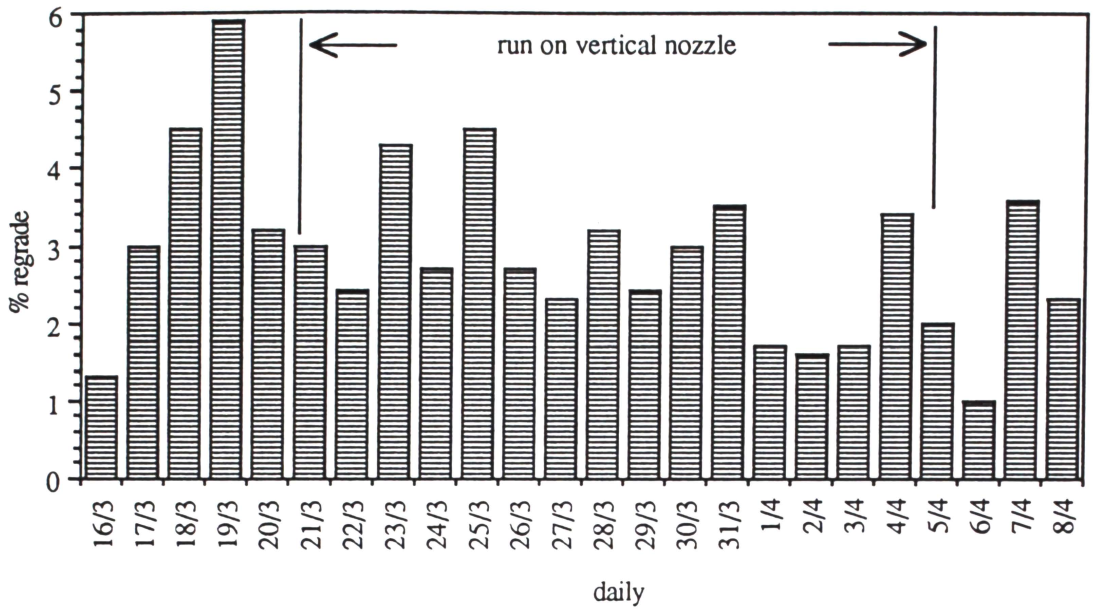


Fig 3.7b Daily Average



3.8.2 Rotated Injection Breach Trial :

The resin injection breach was rotated 180° for a period of two weeks, from the 26/7/91 till 9/8/91, so that the resin was injected into the bulk of the fibre on the far wall of the blowtube. From the results obtained (see fig 3.8a) of this run it appears that the rotation of the resin breach had no affect on the amount of resin spotting; the average amount of resin spotting was 2.4 %.

3.8.3 Three Nozzle Trial :

The resin was injected through three nozzles for a period of two weeks, from the 12/9/91 till 26/9/91. The subsequent resin spotting data obtained (see figure 3.8 and 3.8b) shows that this had no apparent affect on resin spotting.

FIG 3.8
RESIN SPOT REGRADE JULY - SEPTEMBER 1991
WEEKLY AVERAGE

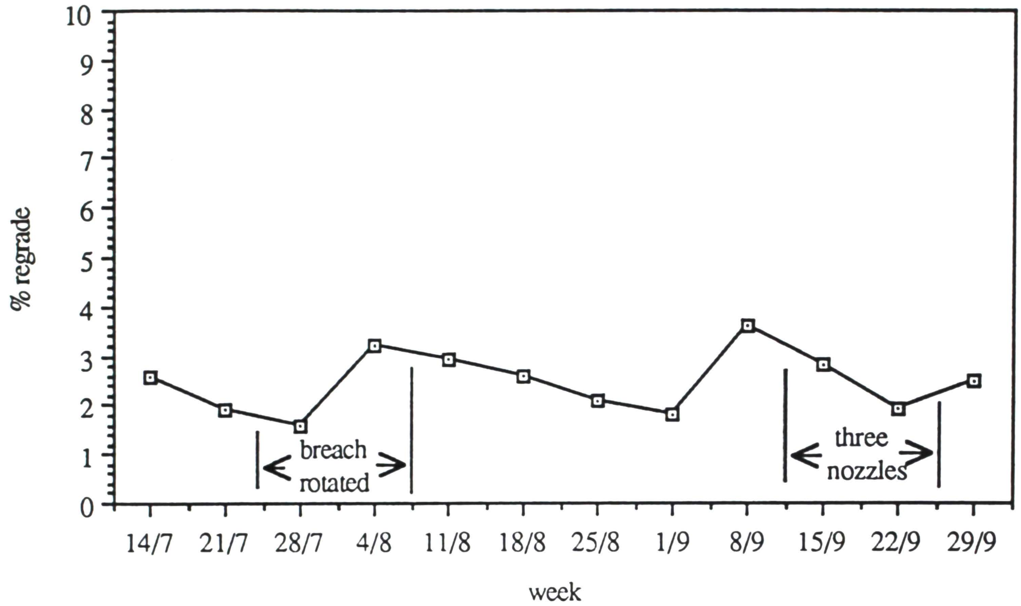


Fig 3.8a RESIN SPOT REGRADE WITH BREACH ROTATED DAILY AVERAGE

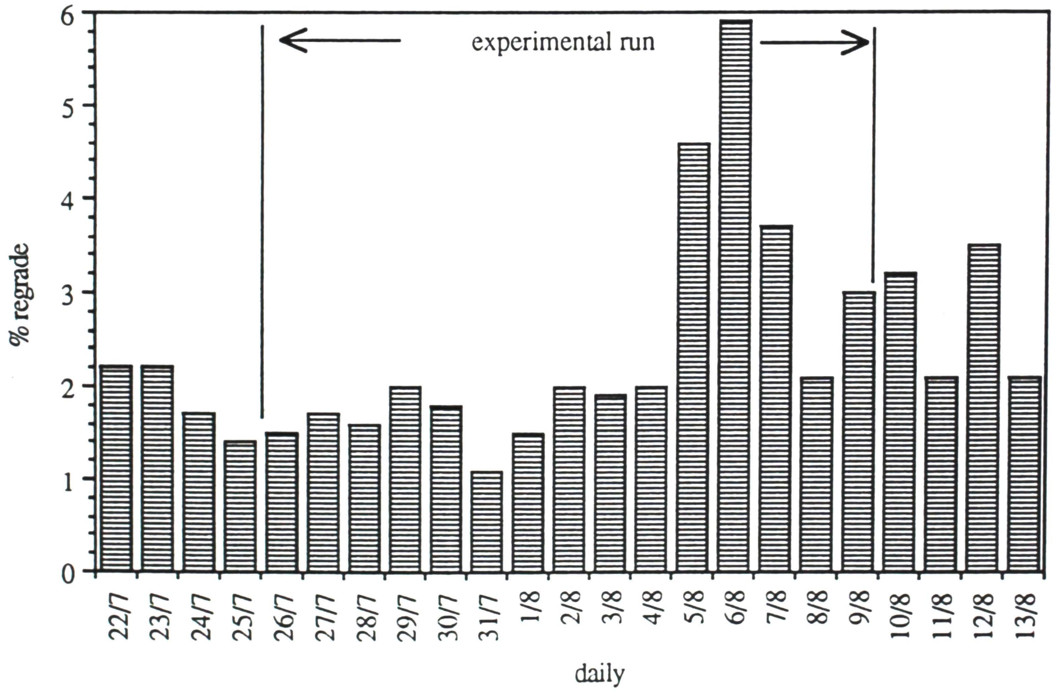
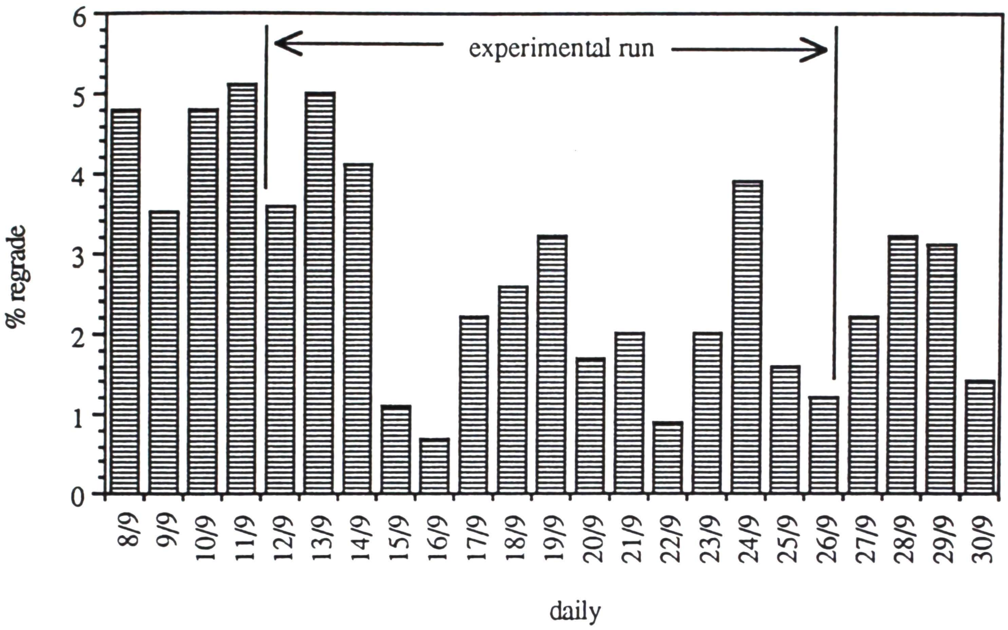


FIG 3.8b
RESIN SPOT REGRADE WITH THREE NOZZLES
DAILY AVERAGE

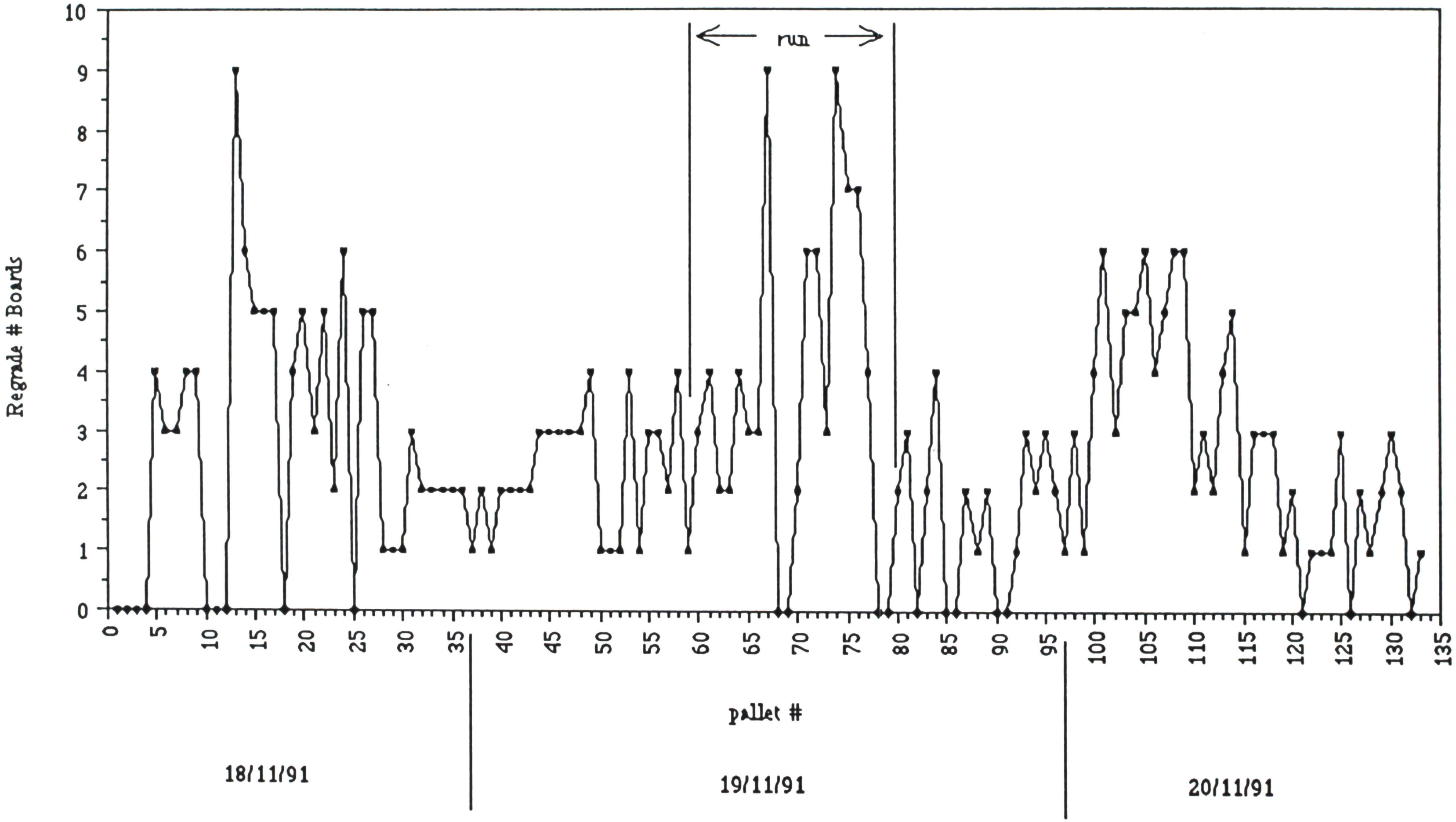


3.8.4 Heated Resin Trial :

The resin was steam heated for short trial periods at first, to ensure there were no adverse affects to production. Results so far obtained seem to indicate that there is no change in resin spotting.

A longer resin heating trial of 8 hours took place on the 19/11/91 and the results (see fig 3.9) indicate that during the trial the regrade due to resin spotting was 6.5 % and was 4.1 % for the rest of that particular 9 mm production run. However a statistical analysis, see Appendix A6 of the data showed that the difference was not significant for the particular production run during which the trial took place.

FIG 3.9
RESIN SPOTTING BY PALLET
(for Heated Resin Trial, Product : 9U740FS)



3.8.5 General Results :

The results of the mixing trials for both the three nozzle experiment and the rotated breach experiment were analysed on a pallet by pallet basis for the periods of change over from normal operation as well as for the maintenance shut which occurred in the middle of both experiments. The figures 3.10 and 3.11 were obtained.

3.9 Separation Experimental Results :

The detailed results of these experiments can be found in Appendix A8, but in summary the average collection efficiency with no fibre being collected was 32%. Typically around 50 grammes of dryer wall material was fed with about the same weight in good fibre being fed. The volume ratios were about 4:1, due to the density difference of the fibre and the wall material. This involved the use of an air curtain to exclude the collection of any 'good' fibre. When no air curtain was used the collection efficiency rose to around 59%, however some fibre, typically around 5 grammes, was collected with this.

FIG 3.10a RESIN SPOTTING FOR 25/7/91

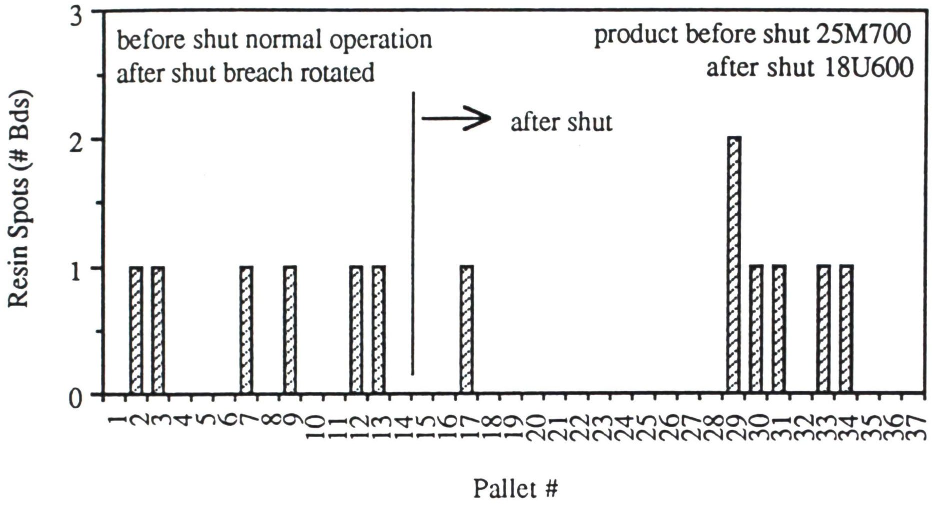


FIG 3.10b RESIN SPOTTING FOR 1/8/91

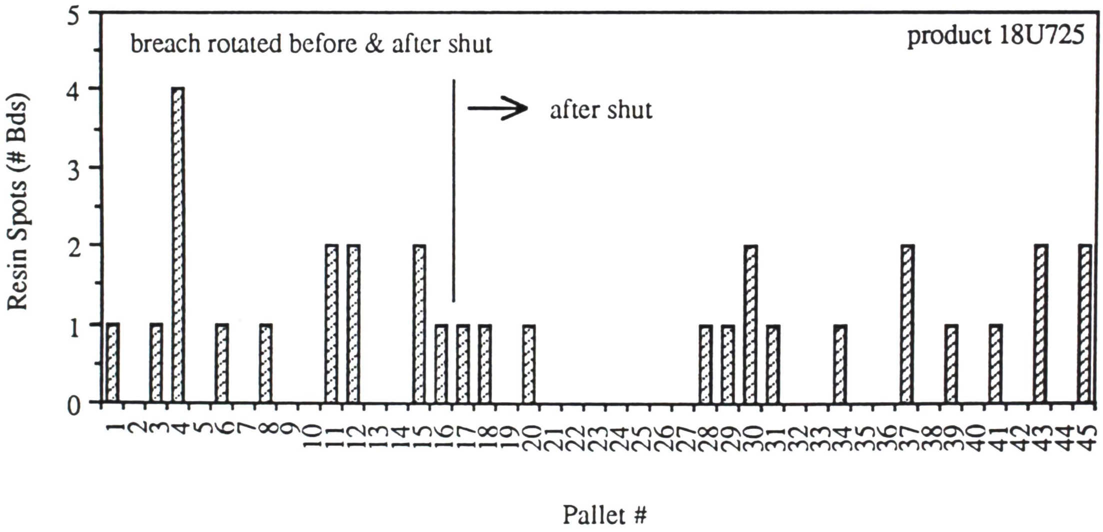


FIG 3.10c RESIN SPOTTING FOR 8/8/91

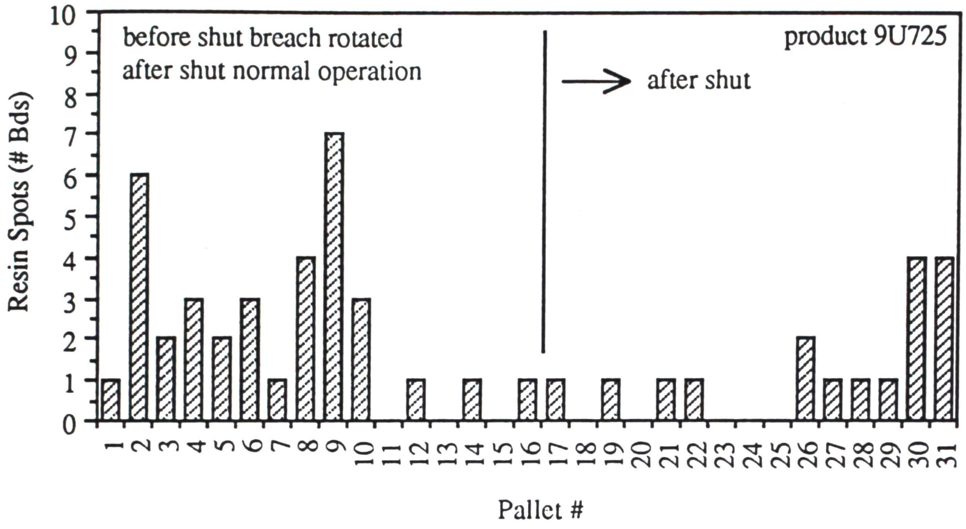


FIG 3.11a RESIN SPOTTING FOR 12/9/91

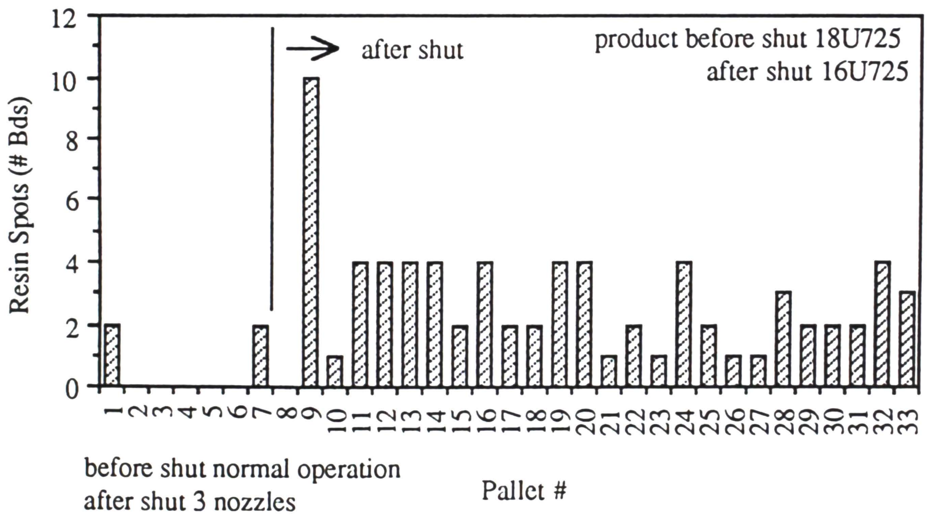


FIG 3.11b RESIN SPOTTING FOR 18/9/91

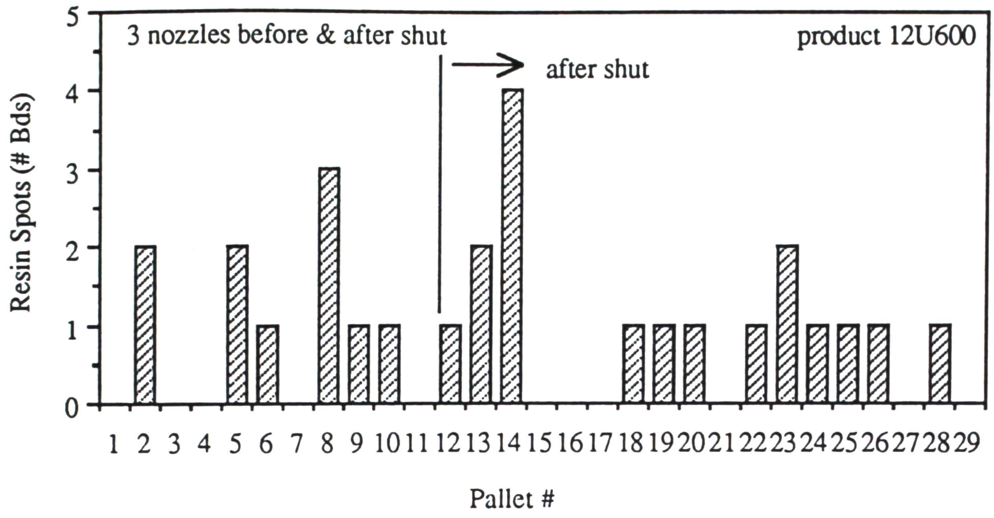
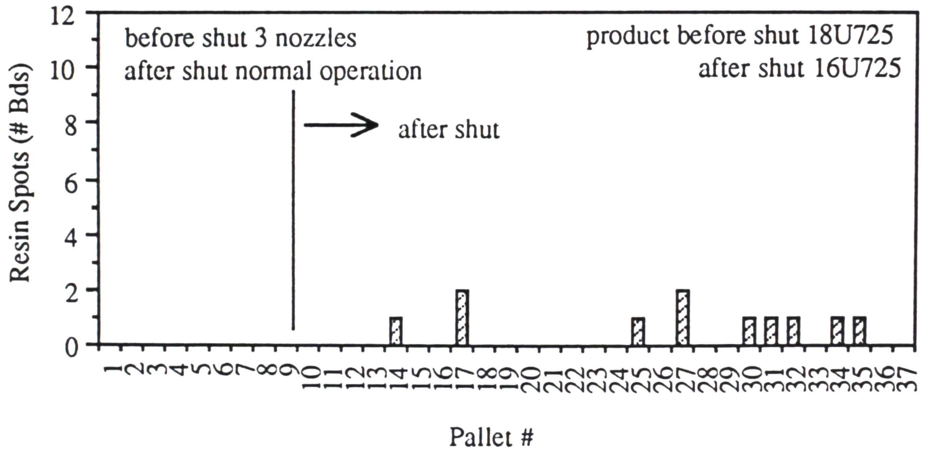


FIG 3.11c RESIN SPOTTING FOR 26/9/91



CHAPTER 4. DISCUSSION

4.1 The Buildup on the Blowtube Wall :

The buildup results tend to suggest that the mere presence of the bolts created a buildup because of the non-continuation of the blowtube wall, ie a smooth wall would stay relatively clean because of the cleaning action of the fibre scraping the wall.

It was deemed impossible to measure the deposit thickness continuously with any form of probe during running of the plant, although a couple of methods were considered. They included the use of a small pitot tube which could be inserted until a velocity increase was recorded and the distance of insertion measured, but problems with this were that there is steam at high pressure and temperature inside the blowtube.

The other method investigated was a heated surface from which the heat transfer rate could be measured and hence the amount of buildup could be calculated as the more the buildup the lesser the amount of heat would be conducted away from the surface. A design for this was developed (see appendix B), but it was discovered that the amount of energy required to be supplied to the probe, to provide a reasonable (10 degrees) temperature difference to measure, was too high (36.4 Watts to a 20 mm diameter probe) to be practical.

4.2 The Buildup on the Dryer Wall :

The long term observations, by the author and the operators, tended to show that there was some dependence on the type of board being produced, in particular the resin content, to the amount of buildup occurring in the dryer, but it was obvious that other unidentified factors were also having an effect on the amount of buildup.

If for example they had a week where the bulk of production was light board, especially if it was thin as well, with a very high resin content, then the buildup in the dryer would tend to be heavier than if the bulk of production was standard board. In general the lower the density the board is the higher the resin content. During the initial period of observation the main type of board produced was standard board, so a "standard" dryer buildup was generally noted.

The buildup in the dryer has in the past been tested and found to be about 5 times higher in resin content than normal board (ref G. Hume private communication). This relates to resin spots having a similar resin content to that of the dryer buildup. They have also been tested and found to be 2-5 times higher in resin content than normal fibre board. This implies resin spotting is a consequence of dryer buildup.

The heat transfer probe designed for the blowtube could possibly be used on the dryer, although probably in a larger form so a larger area of dryer could be sampled. This idea was not thought of at the time the probe was designed and is only an after thought. Actually a heat transfer probe for the dryer would be a lot easier to design and construct as the size limitations are much larger and the same pressures are not present to contend with.

Ways of reducing the dryer buildup were investigated and several ideas were developed. They included cooling the dryer wall, using some form of mechanical cleaning device which could work while the plant is running, providing air jets to stop the wet fibre from contacting the dryer wall, using a flexible wall which could be vibrated to shake the buildup off, or using a non-stick surface such as Teflon.

A piece of sheet Teflon was tried in the dryer for one week without success. The buildup continued on the Teflon just the same. The reason for this, I suspect, being that the Teflon becomes scoured with the action of the fibres which creates pits to which resin and fibre can stick.

The idea of cooling the wall of the dryer to allow condensation to take place and keep the wall wet and hopefully free of buildup was examined. However from rough calculations (see Appendix C) assuming condensation the amount of heat required to be removed was impractical but assuming little condensation (operating just at the dew point) it was practical for a small area. There were a number of other possible related problems in that there was a risk of increasing water spots in the board due to fibre being re-wetted and not drying again by the time it reached the end of the dryer. Also the fact that CTP's dryer is limiting their production and is being run at maximum capacity with the exhaust gas being 100% saturated does not allow for any changes that will effectively reduce the heat duty of the dryer.

For the other suggestions; a vibrating surface would be possible, it would have to withstand the temperature, be flexible and be done over a significant proportion of the dryer. Similarly air jets would have to be used over a large area of the dryer wall and the air would have to be heated to the same temperature as the dryer air to avoid condensation occurring inside the dryer. Both of the previous two methods would have to be done over the same area that buildup is encountered at present, which is about 4 metres before and 2 metres after the first bend in the dryer, from the author's observations. Another possiblilty is to introduce a second flow of hot air at, or just before, the bend in the dryer, however this would have to be investigated further as any change to the current velocity would change the drying of the fibre. Utilising a mechanical device to clean the dryer wall would be difficult because of the shape of the dryer, in particular the bend, and buildup on the device itself is undesirable. As well as it would have to withstand the conditions inside the dryer and be completely automatic. Finally, the use of continuous rotating strips inside the dryer is yet another possibility, but whether buildup will occur on these or not is not known and the mechanical design would not be simple.

4.3 Resin Jet Analysis :

The resin mixing mechanism with the fibre is one of the crucial factors in this investigation and we have been able to observe this through the window well, although the photography of the resin jet has not been easy. We have been able to observe that the resin jet, in the current arrangement, does penetrate approximately 60% of the way across the blowtube, which agrees with the value calculated from theory. Also occasionally some fibre will be in the path of the resin jet and plough into it, hence getting soaked in resin and having a very high resin content. This may, if it does not stick to the dryer wall first, form into a ball of high resin content fibre which will either drop out in the drop-out boxes, if large enough, or go through and be pressed into the board possibly causing resin spots.

As an aside, the dark brown colour of the resin spots and of the blowtube wall buildup, is actually caused by the hydrolytic degradation of the resin, which occurs with the presence of moisture and/or acids, especially at moderate to elevated temperatures; thus at ambient temperatures the rate of breakdown of the resin structure is extremely slow, but at temperatures above 40° C resin deterioration accelerates, and above 60° C the process is very rapid [ref Pizzi p5-6]. In another chapter (p96-97) Pizzi mentions in relation to the curing that the viscosity of the

UF resins changes, not only at a different rate, but also in a different manner according to the temperature. The viscosity gradually increases with temperatures of up to 50°C, above 60°C the viscosity quite quickly reaches a maximum, and then decreases, (see fig 4.1). This indicates that the resin tends to degrade under prolonged heating at high temperatures. Under normal operation when the fibre and resin mix passes straight through the dryer the time, about 2 second, and estimated temperature, about 50°C (ref Gran 1982), is not long or high enough for curing of the resin to occur. However, if the resin and fibre mix sticks to the wall of the dryer both the time and the temperature will dramatically increase and the resin is very likely to cure and/or degrade to some extent.

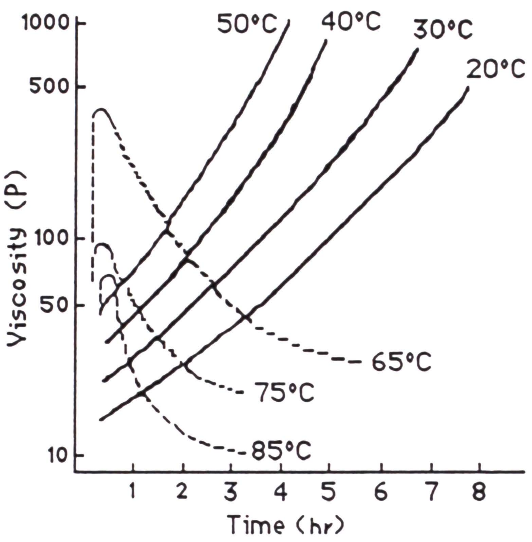


Fig 4.1 Viscosity of a typical UF resin as a function of time at different temperatures, taken from Pizzi.

The resin jet penetration measurements obtained match the theory of a jet being injected into a stream at right angles. The higher the velocity of the jet in relation to the stream velocity the further the jet will penetrate the stream (eg. for a resin flowrate of 25 litres per minute the resin jet is calculated to penetrate about 55% of the diameter of the blowtube and at 50 l/min 85%). The disparity between the predicted and the actual results is no larger than the the differences between the different methods used to obtain the predictions. Schetz and Padhye based their prediction on their own experimental work of injecting water into an air stream at velocities of 0.45 and 0.75 Mach (148.5 and 247.5 m/s respectively) using both circular and rectangular injectors in crossflow at ambient temperatures.

Viswanathan, however, based his prediction on measurements he made from a venturi scrubber using water injected into air at ambient temperatures but at much lower velocities; and Adelberg made his prediction from a theoretical analysis and compared his results with experimental data from 180 cases with 8 liquids at both sub and super sonic flows. It was anticipated that the results obtained from this work would most likely be closest to Viswanathan's prediction as the actual conditions were more similar to those of his experimental work and this in fact proved true, as can be seen in figure 3.1. The error bars shown in figure 3.1 were estimated from the uncertainties in the penetration distances as measured off the photographs.

4.4 Fibre Distribution in the Blowtube :

The results from the photographic analysis were as expected for the blowtube arrangement with the majority of the fibre being on the outside of the bend. We know from the photographs that 70% of the fibre is in the outside 50% of the blowtube at the point of resin injection, due to the preceding bend that the fibre goes through, (see fig 1.2). The graph data is from an average of forty four photographs which were divided into four horizontal sections. In each of these sections, the fractional area covered by fibre was estimated. The fraction of blowtube that was sampled by the photographs was only about 10% of the diameter of the blowtube, as the depth of focus of the camera was 10 mm. The camera was in general focussed on the middle of the blowtube. The total of all the photographs were averaged and the fibre distribution graph was obtained. The outer sections, of figure 3.2, have been extrapolated so as to obtain an overall picture of the fibre distribution across the entire blowtube, since the window does not allow viewing of the extreme edges of the blowtube. The outside divisions were calculated by fitting a second order polynomial curve to the experimental points and extrapolating.

4.5 Unsteady Flow of Fibre and/or Resin :

From our observations through the window and the photographs taken, as well as the analysis done on the response of a photodiode from light shone across the window, the flow of fibre does not appear to be constant. This is apparent from the photographs, see Appendix D, in which gaps with no fibre are visible. An analysis of all photographs taken, showed that the average gap with no fibre present was about 2 centimetres long, with the maximum gap being 16 centimetres long. There were 4 photographs, out of 200, that had absolutely no fibre present at all.

The gap observed in the photographs is confirmed by the peaks in figure 3.3a. These peaks vary but are typically 1 to 3 milliseconds long, which is the same as that calculated by the gap seen in the photographs of 16 centimetres, (at a velocity of 100 m/s this equates to 1.6 milliseconds).

The results from the photodiode tell us that the variation we are measuring is due to water flow as well as fibre flow, as some variation in response was present with only steam flowing. The variation was very different with fibre flowing compared with just steam flowing, as can be seen by comparing figures 3.3a and 3.3c. The steam only response has a lower amplitude, about 1 to 2 volts, and frequency, 3 Hertz, compared with the fibre flow which has an amplitude of about 4 volts and a frequency of 200 Hertz. However the resin flow as far as we can determine from photographs and observation appears to be steady.

The reason for the unsteady flow of fibre has been discovered (ref Gran 1982) to be due to the screw feeding of the primary refiner and also the fact that the steam pressure in the digester is higher than the pressure in the refiner housing, by about 10%. This causes the fibre to be fed unevenly into the refiner as each time the screw rotates the flute is cleared out with the fibre. Hence the overall result is a pulsing fibre flow.

A remedy for this has been found (ref Wiecke 1984), unfortunately at the expense of refiner throughput. If the pressure ratios between the digester and the refiner were reversed, ie having a higher steam pressure in the refiner housing than the digester, again by about 10%, then there would be no forcing of the fibre through the screw each time the screw rotates.

4.6 Resin Spotting in General :

The major changes in figure 3.4, the monthly averages from February 1987, can be attributed to the following. The significant drop about July - August 1987 is due to the addition of the china man's hat on the dryer end of the blow tube (see fig 2.1). The second refiner was added in January 1989 and it can be noted that in general the resin spotting has increased from that time. However, also the amount of production of light board (with a higher resin content) has increased during this period. The peak during January 1990 was due to the grading procedures that were followed during that period being a lot more stringent than usual. There is no explanation for the dramatic increase in resin spotting in June 1991. Referring again to figure 3.4, the resin spotting for the last four years, a possible cause has recently been found for the general increase in resin spotting from July 1989 overall from just under 2.0% to just under 3.0% was due at least in part to the fact that the 'china man's' hat (see fig. 4.2) that was placed on the end of the blowtube was in fact put back on the wrong way around when it was removed to cut 1.5 metres off the blowtube to effectively increase the length of the dryer. However, since the 'china man's' hat was changed back, no significant improvement in resin spotting has been noted. This is probably due to the removal of the section of blowtube, so that now the 'china man's' hat is too close to the end of the blowtube, (it is now 2 blowtube diameters back from the end of the blowtube, previously it was 17 diameters back from the end).

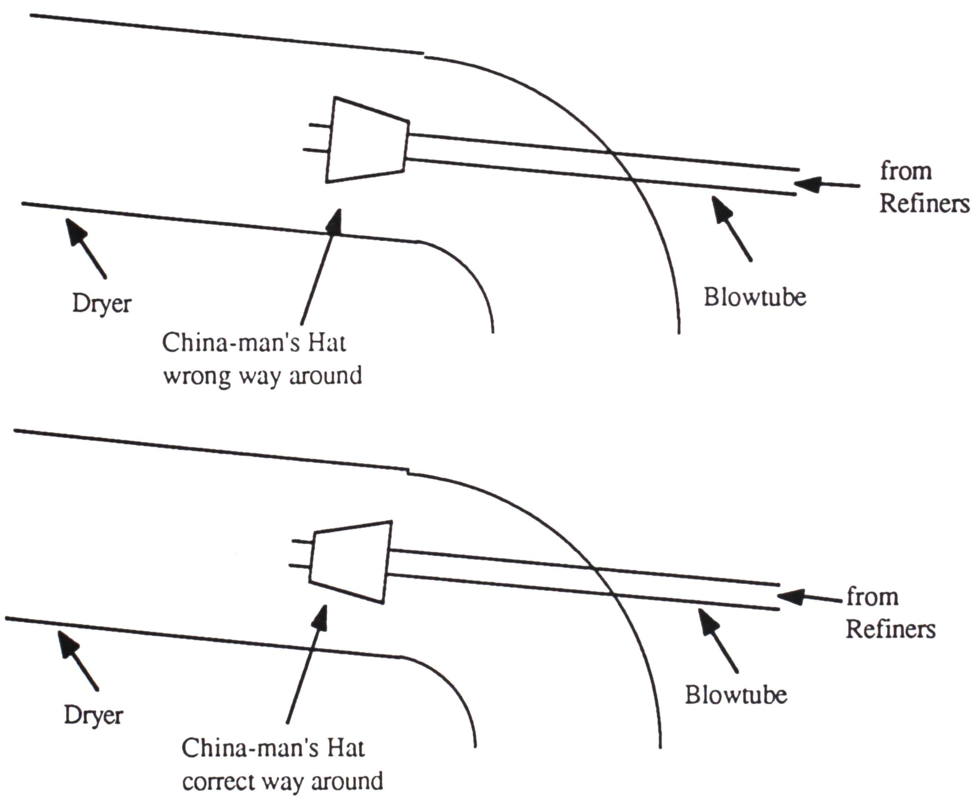
Analysing the resin spot data from 1990-91 it can be seen (see fig 3.5) that in general resin spotting tends to increase with higher resin content (low density) product. The proposed reasons for this is that the higher resin content product causes a higher amount of dryer buildup which leads to more resin spotting. Although resin spotting also appears to increase slightly with thinner products, statistically this is not shown to be significant.(see fig 3.6 and refer appendix A5).

From analysis of resin spotting data on a pallet by pallet basis (see figs 3.10 & 3.11), it appears that the buildup is happening rapidly after start-up from a maintenance shut, as resin spotting is occurring almost immediately, within half an hour of start at least. (Depending on board type, in particular thickness, a pallet consists of normally 3 press loads and takes 30 minutes to produce). This is in spite of the fact that the dryer is cleaned out completely.

As an aside, the curing rate of resin is given (ref Snell & Hilton) as 1 minute at 170^{o}C falling to 8 minutes at 140^{o}C. Extrapolating from this data, the curing time for the resin on the dryer wall, at the estimated temperature of 100^{o}C at the first bend, would be 17 minutes.

Therefore, if resin spotting was caused by dryer buildup, the time for resin spotting to first occur, via cured material coming from the wall, after a maintenance shut would be a minimum of about 17 minutes. It is possible that material could come off the dryer wall once the viscosity fell far enough (see figure 4.1) as the viscosity has been shown, (ref Pizzi), to fall at high temperatures after some time. However, if on the other hand the resin spotting was due to the mixing mechanism of the resin and the fibre, resin spotting would be expected to occur immediately after startup and also would probably be continuous. We know this is not the case, (from figures 3.10 & 3.11), as large gaps do appear with no resin spotting at all. Alternatively,if resin was building up in the blowtube the curing time would be only 1 minute, as the temperature in the blowtube is about 170^{o}C,and resin spotting could be expected to happen almost immediately, within 1 minute, after a startup if it was due to resin building up in the blowtube.

Fig. 4.2 CHINA-MAN'S HAT ON BLOWTUBE IN DRYER



Calculations were done, (see Appendix A4), on resin spotting from different possible sources and comparisons made with the actual resin spotting encountered. This was done for fibre colliding with the resin jet in the blowtube before the jet has broken up and the theoretical amount of resin spotting was calculated to be 1.8 cubic metres per hour of spot material. This compares with the estimated total actual resin spot production of only 0.09 cubic metres per hour and an instantaneous dryer buildup of only 0.04 cubic metres. The instantaneous dryer buildup relates to the rate by the time constant of appearance of resin spotting, ie less than 30 minutes, see P.46. So there would be two renewals in 1 hour, therefore $0.04 \times 2 = 0.08\ m^3/hr$, which is very close to the estimated resin spot production rate. This aggreement strongly supports the mechanism of spotting originating from buildup on the dryer wall. The accuracy of the calculations is not known and would be very difficult to test. However, the amount of resin spot production calculated from the fibre colliding with the resin jet is likely to be an over estimation as effects such as mixing, breaking up of any fibre lumps and the removal of some fibre lumps by separation in the "drop-out" boxes, was not taken into account.

One simple experiment, which was not actually done in this project, was to place on a mat in the production line some dryer wall buildup material and some wet resin and then examine the finished board to see if the resulting marks look like the resin spots encountered in normal production. This would have confirmed that the spots do in fact originate from the dryer wall buildup.

4.7 Photographs in General :

About two hundred photographs in all were taken of the resin and fibre in the blowtube through the window in the resin injection breach. Some examples are shown in Appendix D, (see page 71). It was found, by trial and error, that the best results were obtained by taking the photographs from underneath looking up through the bottom window, with lighting also being provided from below. Depending on the focal distance, and to some extent the flow patterns present in the blowtube, different sections of the blowtube could be observed. Hence the differences in the photographs shown in the appendix. In general the focal distance was set to approximately the centre of the blowtube to try to photograph the resin jet and also to obtain the general fibre distribution in the blowtube, but other focal distances were also attempted. In particular, the last two photographs (photos D-9 & 10), were focused on the closest window and clumps of fibre are clearly obvious. These clumps are visible in the other photographs but only as dark out of focus patches.

4.8 Experiments on the Mixing Mechanism :

4.8.1 Vertical Nozzle Trial :

The idea behind this trial was to inject the resin in an area that was relatively free of fibre so that the jet had a chance to breakup into small droplets before contacting the bulk of the fibre. However the results showed no change in the amount of resin spotting either on a weekly basis or on a daily basis.

The reason there was no change in the resin spotting, which only came to light since the profile of the fibre distribution was determined, may have been that the vertical resin nozzle position was actually injecting the resin in an area that had approximately the same fibre concentration. Referring to figure 3.2, the normal resin nozzle position injected the resin to about the section labelled number 3 and the new resin nozzle position injected the resin to about the position number 1.5, these both have roughly the same fibre concentration of about 0.4 ± 0.02 . Therefore, realistically no change in the resin spotting could have been expected assuming that the concentration of fibre passing the jet has an affect on the amount of resin spotting.

4.8.2 Rotated (180^o) Injection Breach Trial :

This was done to try to determine if the resin mixing mechanism has any effect on the amount of resin spotting. The idea being that the mixing mechanism would change by injecting the resin into the bulk of the fibre on the far side of the blowtube. Photographs were taken through the windowed breach but they were not very successful and did not show the resin jet clearly.

Unfortunately at the same time a screw extraction system was put on the first drop-out box to continuously remove the material collected there and this was likely to have an effect on the amount of resin spotting, (this was part of a separate project). However from the results obtained it appears that there has been no significant affect on resin spotting at all, even after the injection breach was rotated back to it's original position and the screw extraction system was left in place. Hence neither modification had any effect on resin spotting.

4.8.3 Three Nozzle Trial :

The results from this experiment again showed no significant change in resin spotting, the average over the whole trial being 2.4%. So a more evenly spread resin and fibre mixing mechanism is not an advantage.

4.8.4 Heated Resin Trial :

Similarly for this experiment, particularly looking at the longer trial, there was no major change in the amount of resin spotting. The resin during this trial was injected through only one nozzle as that was all the heater was designed to accept. The one problem that was discovered with this experiment was that if the steam flow got too high it would start pulsing, however this fortunately did not start to happen until the resin temperature got above about 70^{o}C. This was one reason for keeping the resin temperature at 60^{o}C. The other was that indications from the literature, (ref Pizzi), showed that the resin will degrade rapidly at temperatures above 60^{o}C. If a higher temperature of resin was required the heat exchanger would have to be changed from being a simple direct injection to a proper shell and tube type.

Hence reducing the resin viscosity to allow for an easier and smaller breakup of the resin jet is not an effective option for reducing the amount of resin spotting.

4.8.5 General Mixing Mechanism Results :

The results obtained tend to indicate that the mixing mechanism has no effect on the amount of resin spotting and hence the resin spotting is almost certainly to be caused by the buildup that occurs in the dryer. Also the fact that other board properties, in particular board Internal Bond (I.B.), have not changed significantly during our trials would seem to indicate that the degree of mixing of the fibre and the resin is not changing. It was also noted that none of the mixing mechanism experiments had a detrimental effect on the amount of resin spotting, ie they did not make it significantly worse.

4.9 Resin Nozzle Design :

Changes in the shape of the resin nozzle to alter the spread of resin injected into the blowtube have been contemplated. However, a successful alternative design was not developed. The major problem has been that of keeping the nozzle clear from blockages. It has been discovered from past plant experience that if there is no cleaning probe the nozzle will tend to block and hence become useless. Therefore the most practical and simple nozzle is that which is used at present (see fig 2.3) a straight through nozzle with a cleaning probe, with the only possible easy changes being in the diameter.

4.10 Separation Experiments :

The results of the experiments showed that the idea was feasible for removing some of the resin spot material from the fibre stream within the dryer. However, collection efficiencies were not very high, being around 32% with no fibre being collected.

This was a simple model of the system and there would be some differences between what happened in the model and what would happen inside the dryer. Factors that were not taken into account included the concentration of the resin spot material in the fibre stream and how well it would be entrained. Also the dryer could not be exactly modelled as although the velocities used in the model were of a similar magnitude to that in the dryer, the Reynolds Number was completely different. However, the length of dryer available for gravity separation of the resin spot material would be more than adequate based on the terminal velocity of the resin spot material compared with that for 'good' fibre. Dryer buildup material, which is taken to be similar to resin spot material, falls at 2.8 metres per second and hence would take only 0.3 s to fall 0.75 metres (half the diameter of the dryer) and at a dryer velocity of 24 metres per second, would travel 7.2 metres, which is approximately half of the length of dryer from the second bend. In the model the comparative figures are; the resin spot material would take 0.02 of a second to fall 50 mm (half the diameter of the tube) and would travel 0.41 of a metre, approximately one third of the length of the collector tube. Calculations based on the results obtained from the model indicate that collection efficiencies of about 30% could be anticipated in the dryer if a similar system to the model was implemented.

The results also demonstrated that an air curtain would be essential to exclude the collection of any 'good' fibre. However calculations determined, (see Appendix A7) that depending on the amount of air injected into the dryer from the air curtain it would have to be heated otherwise condensation may occur in the dryer. This is mainly due to the fact that CTP's dryer is currently operating at its limit and the exhaust air is completely saturated.

CHAPTER 5. CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions :

Our experiments, as well as the results of this study, appear to indicate that the mixing mechanism has no direct affect on resin spotting, as none of our mixing mechanism experiments that were carried out showed any change in the amount of resin spotting being obtained. It is the author's opinion that it is unlikely that the buildup on the blowtube wall is the major cause of resin spotting as any buildup there appears to be well stuck and is very difficult to remove and hence will not peel off under normal operating conditions. It is believed that the reason buildup occurs less, in relative quantity, in the blowtube is due to the high velocities and the fact that any resin that comes in contact with the blowtube walls is likely to be wiped off by the fibre.Therefore, the more likely cause of resin spotting is from the dryer buildup. This is confirmed by the fact that the rates of turnover of dryer buildup and estimated actual resin spot production match. The reason being that when the resin and fibre builds up on the dryer wall the residence time dramatically increases and the resin has a chance to cure and/or degrade at the elevated temperatures inside the dryer. It was determined, from literature, that the basic cause of resin spotting is the degradation of the resin and this occurs when the resin is subjected to elevated temperatures in the presence of moisture and/or acidic conditions for relatively long periods of time. This occurs when resin builds up on the dryer walls.

It is apparent that the only way to eliminate resin spotting is to prevent buildup from occurring on the dryer walls. However, this is no easy task especially with the current dryer and although various methods, including cooling the walls of the dryer, have been examined no practical solution has been discovered. The problem is confounded by the fact that the fibre as it passes through the dryer goes around a 'U' bend and will collide with the walls, and this can not be avoided.

The results of the resin jet analysis show that theoretical methods can be used to predict the jet penetration distance, for a jet injected at right angles to a high velocity stream, in an industrial application with reasonable accuracy.

Initial separation experiments were carried out at the University of Canterbury, with only a moderate degree of success, to test the feasibility of removing the resin spot material from the fibre stream inside the dryer. This method of reducing resin spotting would require further investigation to determine whether in fact it would be feasible and if significant reductions in resin spotting could be expected. It is anticipated that a separator after the dryer could in fact produce a better separation of resin spot material and 'good' fibre than one incorporated into the present dryer as a longer residence time than that available in the dryer could be utilised. The separator would probably have to be very large, possibly of the order of 24 m^3, giving a residence time of about 2 seconds. The residence time currently available in the last leg of the dryer is approximately 0.6 of a second and it is questionable whether this is sufficient to provide a reasonable separation between the resin spot material and the 'good' fibre.

5.2 Recommendations :

The recommendations from this investigation for the reduction of resin spotting in MDF is to utilise a separator to remove the resin spot material from the fibre stream after it has passed through the dryer.

It is therefore recommended that a design similar, but vastly improved, to the current drop-out box be employed as a separator to remove the resin spot material from the fibre stream.

From the limited knowledge of other MDF plant operations it appears that gravity separators are used to reduce resin spotting with some degree of success, the amount of which is not known. It has also been noted by the author that separators have been designed and are available from the major MDF plant suppliers and designers.

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APPENDICES

APPENDIX A

A1. Jet Penetration Calculations :

The following three equations were used to predict the jet penetration distance into the blowtube, so a comparison with the actual results could be made.

Schetz & Padhye Calculation :(ref Schetz & Padhye)

$$\frac{h}{d_f} = 13.5\,(\bar{q})^{1/2}\,C_d\left[\frac{d_{eq}}{d_f}\right]^2\left[\frac{d_f}{d_s}\right]^{0.416}$$

where

h = penetration distance, mm

d_f = frontal injector dimension, mm

$\bar{q} = \rho_j V_j^2 / \rho_\infty V_\infty^2$

= momentum flux ratio

C_d = discharge coefficient = 0.4 (ref Adelberg p 1411)

d_{eq} = equivalent injector diameter, mm

d_s = sidewise injector dimension, mm

Note : for a circular injector $d_f = d_{eq} = d_s$

Adelberg Calculation : (ref Adelberg)

$$y_0 = \frac{2\,D_0^{1/2}}{n\,j_0}\left[\frac{\frac{1}{2}\rho_j V_j^2}{\frac{1}{2}\rho_g V_g^2}\right]\left[\frac{\sigma}{\rho_j V_j^2}\right]^{1/2}$$

where

y_o = maximum penetration distance of jet

D_o = diameter of jet at inlet

$n = \rho_g V_g^2 / \overline{\rho_g V_g^2} \approx 1$

j_o = constant = 4.0×10^{-3}

ρ_j = density of liquid jet

ρ_g = density of gas stream

V_j = velocity of liquid jet

V_g = velocity of gas stream

σ = surface tension

Viswanathan Calculation :(ref Viswanathan)

- for maximum penetration :

$$\frac{l^{**}}{d} = 0.1145 \frac{\rho_j V_j}{\rho_g V_g}$$

- and for break-up penetration :

$$\frac{l^{*}}{d} = 0.1015 \frac{\rho_j V_j}{\rho_g V_g}$$

where

l^{**} = maximum penetration distance
l^{*} = penetration distance to break-up
d = diameter of jet orifice
ρ_j = density of liquid jet
ρ_g = density of gas stream
V_j = velocity of liquid jet
V_g = velocity of gas stream

Jet Penetration Data :

Diameter of jet(mm)	7
Density of resin(kg/m^3) @ 20C	1405
Viscosity of resin(cP) @ 20C	60
Surface tension(dynes/cm) @ 20C	30
Density of steam(kg/m^3)	2.81
Velocity of stream(m/s)	100
Area of jet(m^2)	3.85E-05
Adelberg constant	41.83

Jet Penetration Calculation Results :

Resin Flowrate(L/Min)	Velocity (m/sec)	Schetz & Padhye Theory q=Pj*Vj/Ps*Vs	h (mm)
15	6.50	2.1100	54.91
20	8.66	3.7511	73.21
25	10.83	5.8611	91.51
30	12.99	8.4399	109.81
35	15.16	11.4877	128.12
40	17.32	15.0043	146.42
45	19.49	18.9898	164.72
50	21.65	23.4442	183.02
55	23.82	28.3675	201.33
60	25.98	33.7597	219.63

Resin Flowrate(L/Min)	Velocity (m/sec)	Visvanathan L** (mm)	L* (mm)	Adelberg Yo (mm)
15	6.50	26.03	23.08	19.85
20	8.66	34.71	30.77	26.47
25	10.83	43.39	38.46	33.09
30	12.99	52.07	46.15	39.71
35	15.16	60.74	53.85	46.33
40	17.32	69.42	61.54	52.95
45	19.49	78.10	69.23	59.56
50	21.65	86.78	76.92	66.18
55	23.82	95.46	84.62	72.80
60	25.98	104.13	92.31	79.42

A2. Droplet Size Calculation :

(Ref Nukiyama & Tanasawa (1939a))

This equation was used to calculate the droplet size of the resin after it is broken up when injected into the blowtube. This was done to compare the size of droplet from the heated and non-heated experiments.

$$d_{32} = \frac{585}{v_r}\sqrt{\frac{s}{r_l}} + 597\left[\frac{m}{\sqrt{s\,r_l}}\right]^{0.45}\left[\frac{1000\,Q_l}{Q_g}\right]^{1.5}$$

where

d_{32} = Sauter mnn diameter, microns

r_l = density of liquid, g/cc

s = surface tension, dynes/cm

m = viscosity of liquid, poises

v_r = relative velocity of gas and liquid, m/s

Q_l = liquid volumetric flow rate

Q_g = gas volumetric flow rate

Density of resin(kg/m^3) @ 70C	1376
Viscosity of resin(cP) @ 70C	1
Surface tension(dynes/cm) @ 70C	25
d32 (microns) @ 20C =	269.3
d32 (microns) @ 70C =	45.3

A3. Photograph Analysis of Fibre Distribution in the Blowtube

The average fibre concentration across the blowtube was calculated by analysising 44 photographs. Each photo was divided into four sections and the fractional area covered by fibre was calculated. The total of all the photographs was averaged and the graph was obtained. The four divisions on either side were estimated by extrapolation as they could not be photographed, (only the middle third of the blowtube was observable through the window).

Estimate of Division 0	30%
Estimate of Division 1	30%
Estimate of Division 2	31%
Estimate of Division 3	32%
Division 4	33%
Division 5	35%
Division 6	51%
Division 7	71%
Estimate of Division 8	85%
Estimate of Division 9	95%
Estimate of Division 10	99%
Estimate of Division 11	100%

A4. Resin Spot Production Calculation :

1. From Fibre Colliding with Resin Jet in Blowtube before Jet has Broken up :

assume jet penetrates 45% of blowtube before breaking up	
also jet expands at 15 degree included angle	
area of jet : rectangle + 2 triangles	
rectangle = penetration distance x diameter of jet =	315
triangle - h = penetration distance (mm)=	45
triangle - b = 45 tan 15 =	12
1/2b.h. =	270
area of jet (mm^2)=	855
diameter of blowtube (mm)=	100
area of blowtube (mm^2)=	7854.0
area relevant to jet (mm^2)=	3534.3
fraction of area covered by resin jet (mm^2)=	24.19%
amount of fibre in first 45% of blowtube =	
from fibre distribution graph = sections 0-2 =	31.20%
hence fraction of fibres colliding with resin jet =	7.55%
fibre mass flow (kg/s) =	3.0
assumed average fibre volume (m^3) =	3.2E-12
assumed average fibre weight (kg) =	1.44E-09
no. of fibres per kg =	2.08E+09
volume (m^3) =	6.67E-03
hence volume of fibres colliding with resin jet (m^3/s)=	5.03E-04
volume in 1 hr (m^3)=	1.81

2. Estimated Actual Resin Spot Production :

Average of boards downgraded with resin spots =	2.50%
Average board thickness (mm) =	18
Assume resin spot size, area (mm^2) =	100
Assume resin spot thickness, (mm) =	1
Probability of resin spot being on surface =	0.11
hence actual no. of boards (per 100) with resin spots =	22.5
quantity of resin spots (mm^3) =	2250
average production rate (m^3/hr) =	13
board size (m^3) = 7.2m x 2.4m x 18mm =	0.31104
hence production rate (boards per hour) =	41.8
hence resin spot production (m^3/hr) =	0.0940
resin spot rate of production (no. spots per hour) =	9.40
or on average one spot every : (minutes)	6.38

3. Estimated Dryer Buildup Volume (instantaneous) :

Dryer diameter (m) =	1.5
Approx length of dryer in which build-up occurs (m) =	4
hence area (m^2) =	19
thickness of build-up, estimated (mm) =	2
hence volume of build-up (m^3) =	0.04

A5. Resin Spot Data Statistical Analysis

1. Resin Content versus Regrade Statistics :
(data from 1990-91 plant records)

Resin Content (%)	Regrade (%)
8.5	3.6
9	2.7
9.5	.9
11.5	.8
13	1.8
15	3.6
15.5	2.6
16	5.3
17	3.1
17.5	6.8

therefore as $t_{\alpha/2,n-2} = t_{0.05,8} = 1.812$ and $|t_0| > t_{0.05,8}$ the hypothesis that the slope = 0 is rejected.(Note $|t_0|$ = t-Value in the table = 2.025).

Simple Regression X_1 : Resin Content Y_1 : Regrade

DF:	R:	R-squared:	Adj. R-squared:	Std. Error:
9	.582	.339	.256	1.607

Analysis of Variance Table

Source	DF:	Sum Squares:	Mean Square:	F-test:
REGRESSION	1	10.593	10.593	4.101
RESIDUAL	8	20.663	2.583	p = .0774
TOTAL	9	31.256		

Residual Information Table

SS[e(i)-e(i-1)]:	e ≥ 0:	e < 0:	DW test:
33.808	4	6	1.636

Simple Regression X_1 : Resin Content Y_1 : Regrade

Beta Coefficient Table

Parameter:	Value:	Std. Err.:	Std. Value:	t-Value:	Probability:
INTERCEPT	-1.076				
SLOPE	.317	.156	.582	2.025	.0774

Confidence Intervals Table

Parameter:	95% Lower:	95% Upper:	90% Lower:	90% Upper:
MEAN (X,Y)	1.948	4.292	2.175	4.065
SLOPE	-.044	.677	.026	.608

2. Board Thickness versus Regrade Statistics :

(data from 1990-91 plant records)

Board Thickness (mm)	Regrade (%)
7	3.4
7.5	2.4
8	2.5
9	4.4
12	3
15	3.3
16	2.8
18	2.4
19	1.9
20	2.5
21	4.1

therefore as $t_{\alpha/2,n-2} = t_{0.05,8} = 1.782$ and $|t_0| < t_{0.05,8}$ the hypothesis that the slope = 0 can not be rejected.

(Note $|t_0|$ = t-Value in the table = 0.461).

Simple Regression X_1 : Thickness Y_1 : Regrade

DF:	R:	R-squared:	Adj. R-squared:	Std. Error:
10	.152	.023	-.085	.799

Analysis of Variance Table

Source	DF:	Sum Squares:	Mean Square:	F-test:
REGRESSION	1	.136	.136	.213
RESIDUAL	9	5.746	.638	p = .6557
TOTAL	10	5.882		

Residual Information Table

SS[e(i)-e(i-1)]:	e ≥ 0:	e < 0:	DW test:
10.2	4	7	1.775

Simple Regression X_1: Thickness Y_1: Regrade

Beta Coefficient Table

Parameter:	Value:	Std. Err.:	Std. Value:	t-Value:	Probability:
INTERCEPT	3.274				
SLOPE	-.022	.047	-.152	.461	.6557

Confidence Intervals Table

Parameter:	95% Lower:	95% Upper:	90% Lower:	90% Upper:
MEAN (X,Y)	2.428	3.518	2.531	3.414
SLOPE	-.128	.085	-.108	.065

A6. Heated Resin Experimental Results Statistical Analysis.

Total of all Pallets in Complete Production Run

X1: r/g bds

Mean:	Std. Dev.:	Std. Error:	Variance:	Coef. Var.:	Count:
2.654	2.049	.178	4.198	77.193	133
Minimum:	**Maximum:**	**Range:**	**Sum:**	**Sum Squared:**	**# Missing:**
0	9	9	353	1491	0
t 95%:	**95% Lower:**	**95% Upper:**			
.351	2.303	3.006			

Total of all Pallets in Heated Resin Run

X_2: r/g bds 2

Mean:	Std. Dev.:	Std. Error:	Variance:	Coef. Var.:	Count:
3.7	2.849	.637	8.116	76.995	20
Minimum:	**Maximum:**	**Range:**	**Sum:**	**Sum Squared:**	**# Missing:**
0	9	9	74	428	113
t 95%:	**95% Lower:**	**95% Upper:**			
1.333	2.367	5.033			

$$t_o = \frac{\overline{y_1}-\overline{y_2}}{\sqrt{\frac{s_1^2}{n_1}+\frac{s_2^2}{n_2}}} = \frac{3.7-2.654}{\sqrt{\frac{1491}{133}+\frac{428}{20}}} = 0.183$$

and $t_{\alpha,n1+n2-2} = t_{0.025,151} = 1.960$

hence $|t_0| < t_\alpha$ and cannot show that the two means are unequal.

(Note $|t_0|$ = t 95% in the table = 1.333).

A7. Dryer Air Addition Heat/Condensation Calculations.

Basic calculations were performed to determine if any air added to the dryer, as an air curtain to exclude 'good' fibre from a collector for resin spot material, would have to be heated so condensation would not take place.

The following data was used :

Dryer air data : $V_1 = 36\ m^3$

$\rho_1 = 1.04\ kg/m^3$

$M_1 = 37.44\ kg$

$T_1 = 70^oC$

$Y_1 = 0.15$ kg H_2O/kg dry air

Injected air data : $V_2 = 3.2\ m^3$ (this was computed by scaling up from the separation experiments performed)

$\rho_2 = 1.249\ kg/m^3$

$M_2 = 4.0\ kg$

$T_2 = 20^oC$

$Y_1 = 0.0095$ kg H_2O/kg dry air

$Cp = 1.0467$ kJ/kg.K

Simply :

$M_1.Cp_1.T_1 + M_2.Cp_2.T_2 = M_T.Cp_T.T_T$

$= 14668.37$

hence can calculate $T_T = 65.7^oC$

the moisture capacity of added air

= 0.0055 kg H_2O/kg dry air

= 0.022 kg H_2O total (0.0055 x 4.0 kg)

but air at 65^oC and 100% saturated has 0.12 kg H_2O/kg dry air,

therefore the difference in moisture content between the dryer air and the dryer air plus the added air is = 0.15 - 0.12 = 0.03 kg/kg, over the total mass of air this = 1.12 kg, but the capacity of the added air is only 0.022 kg, hence condensation will occur unless the added air is preheated.

A8 Separation Experimental Results.

1. General :

Size of collection area :

Experiment	A	B
Sector of circle - height (mm) =	30	15
- diameter (mm) =	92	92
Area (mm^2) =	2167.7	1083.8
Diameter of pipe (mm) =	108	108
Area (mm^2) =	9160.9	9160.9
hence collection area fraction =	23.66%	11.83%

2. Settling Rate Measurements :

Resin Spot Material

Height dropped (m) =		2
Times :	Run #	Time (s)
	1	0.78
	2	0.71
	3	0.66
	4	0.67
	5	0.76
	average =	0.716
	velocity (m/s)=	2.79

Fibre

Height dropped (m) =		2
Times :	Run #	Time (s)
	1	1.17
	2	1
	3	1.41
	average =	1.19
	velocity (m/s)=	1.68

3. Velocity Measurements :

Duct velocity (m/s) =	23.3
Duct diameter (mm) =	108
area (m^2) =	9.16E-03
volumetric flow (m^3/s) =	0.213
Air Curtain velocity, (m/s) =	7.9
Air Curtain width (mm) =	20
Air Curtain length (mm) =	120
area (m^2) =	2.40E-03
volumetric flow (m^3/s) =	1.90E-02

4. Collection Results :

Experiment No.	1A	2A	3A
Air Curtain velocity, (m/s) =	0	0	0
Method material fed	thru fan	thru fan	in straightener
Weight of feed container (g) =	10.000	10.000	8.260
Weight of container + material (g) =	95.705	81.374	38.303
Weight of material fed (g) =	85.705	71.374	30.043
Weight of material collected + container (g) =	28.626	30.783	33.995
Weight of collection container (g) =	28.626	28.626	28.727
Weight of material collected (g) =	0.000	2.157	15.268
% collected =	0.0%	3.0%	50.8%
Weight of fibre fed (g) =	0	0	0
Weight of fibre collected (g)	0	0	0

Experiment No.	4A	5A	6A
Air Curtain velocity, (m/s) =	0	0	7.9
Method material fed	in straightener	in straightener	in straightener
Weight of feed container (g) =	9.995	8.260	9.995
Weight of container + material (g) =	44.920	44.245	55.870
Weight of material fed (g) =	34.925	35.985	45.875
Weight of material collected + container (g) =	50.555	51.770	30.751
Weight of collection container (g) =	28.876	28.876	9.995
Weight of material collected (g) =	21.679	22.894	20.756
% collected =	62.1%	63.6%	45.2%
Weight of fibre fed (g) =	48.643	52.607	0
Weight of fibre collected (g)	4.527	3.052	0

Experiment No.	7A	8B	9B
Air Curtain velocity, (m/s) =	7.9	7.9	7.9
Method material fed	in straightener	in straightener	in straightener
Weight of feed container (g) =	8.260	8.260	9.995
Weight of container + material (g) =	49.123	59.545	59.128
Weight of material fed (g) =	40.863	51.285	49.133
Weight of material collected + container (g) =	22.157	22.404	20.252
Weight of collection container (g) =	8.260	8.260	9.995
Weight of material collected (g) =	13.897	14.144	10.257
% collected =	34.0%	27.6%	20.9%
Weight of fibre fed (g) =	55.012	43.502	49.850
Weight of fibre collected (g)	5.894	4.803	5.410

A9. Blowtube Velocity Measurements.

Date	Velocity (m/s)	Blow Valve (% open)	2nd Refiner Pressure (PSI)	Production Rate (m^3/hr)
8/11/90	93	100	81	13.4
8/11/90	91	100	81	13.4
22/11/90	78	80	80	12.8
16/1/91	78	80	80	13.2
16/1/91	78	80	80	13.2
16/1/91	78	80	80	13.2
25/1/91	103	100	84	14.8
30/1/91	86	100	83	14.2

APPENDIX B

For the continuous measurement of the build-up occurring on the blowtube wall a design for a probe based on measuring the heat transfer from the wall was developed. The theory being that the cleaner the wall the higher the heat transfer from the wall and if the temperature of the wall is measured after applying a known amount of heat the amount of build-up can be computed (calibration would be required if exact amount of build-up is required) or just the trend obtained. (For design of probe see figures B-1,2 & 3)

Calculation :

Heat Transfer from Probe :

$\overline{v} = 100$ m/s

$\nu = 33 \times 10^{-6}$ m^2/s for steam @ 450 K

Pr = 1.008 @ 450 K for steam

so :

$$Re = \frac{D.u}{\nu} = \frac{(0.10m).(100\ m/s)}{33 \times 10^{-6}} = 3.0 \times 10^{5}$$

so if surface entirely clean,

use $\quad Nu = 0.023\ Pr^{0.3}\ Re^{0.8}$ (ref Welty)

$= 0.023\ (1.008)^{0.3}\ (3.0 \times 10^{5})^{0.8}$

$= 588$

$k_{(steam)} = 0.032$ W/m.

ie : $\frac{h\ .\ D}{k} = 588$ so $h = \frac{(588)\ (0.032)}{(0.10)} = 176 \frac{W}{m^2K}$

so would want to measure temperature changes of about 10^{o}C, so need perhaps 50^{o}C temperature above ie about 20^{o}C driving temperature difference.

ie : $q = (h.+ k/L)\Delta T = (176 + 22.5/0.004)(20)$

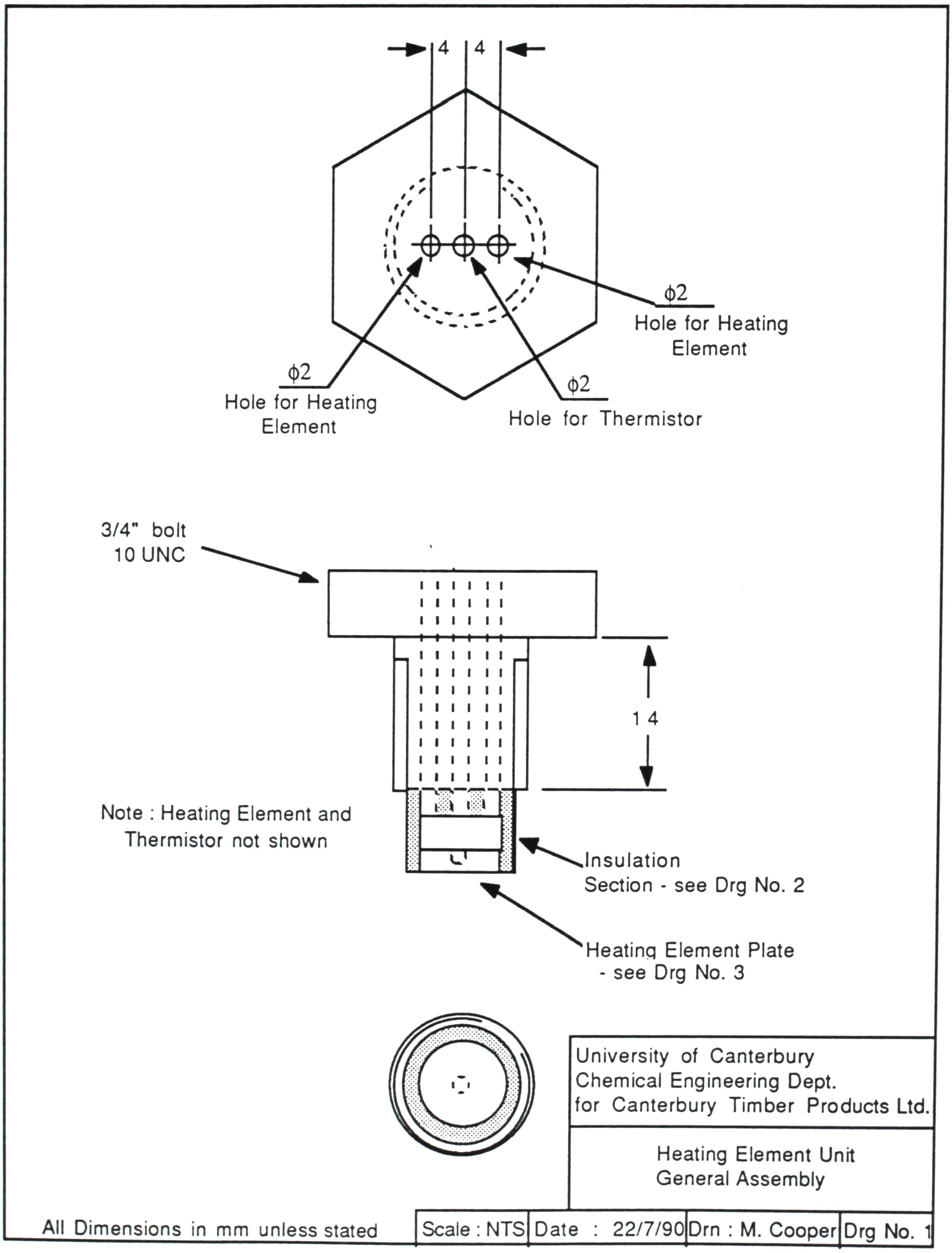
k = heat transfer coefficient for stainless steel, W/m.K

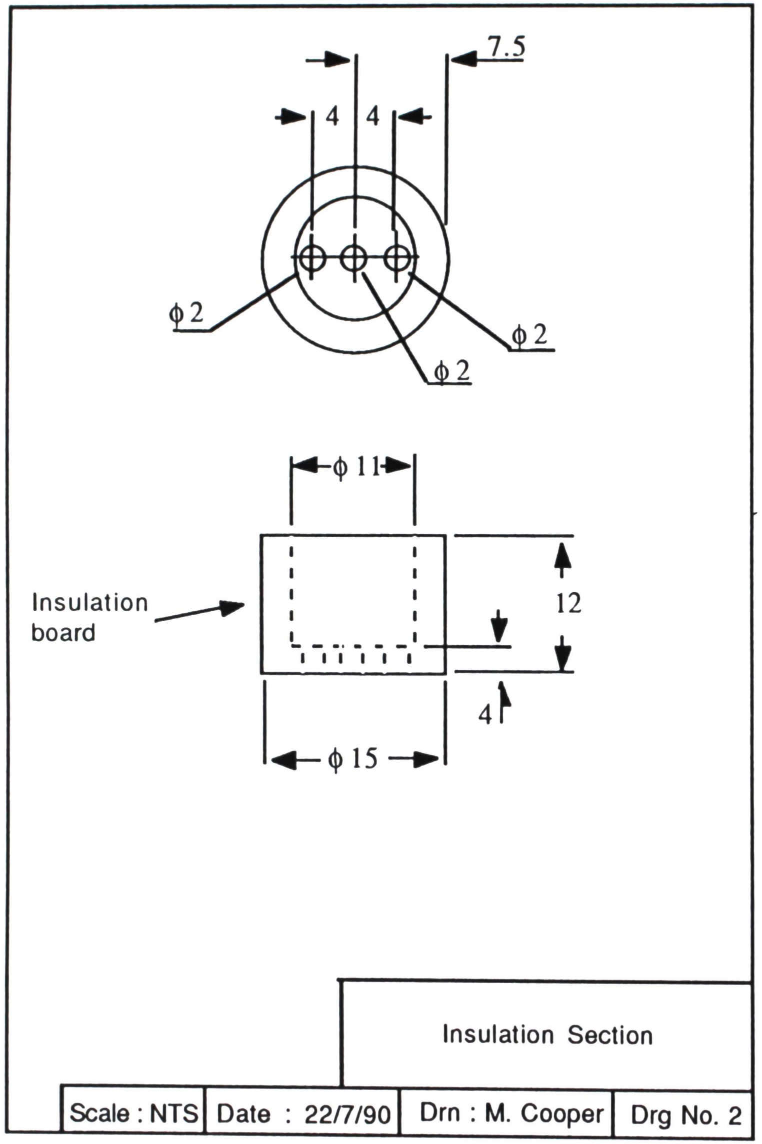
L = thickness of stainless steel, m

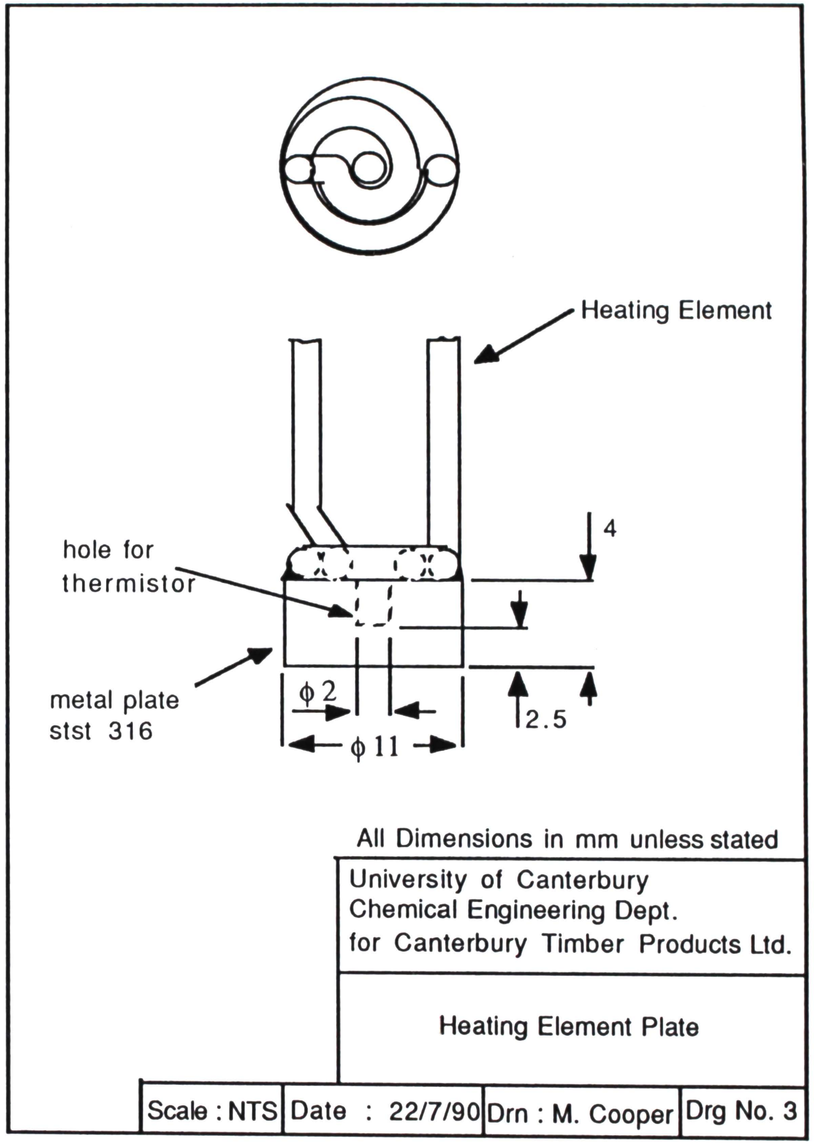
(20 mm diameter sensor)

ie : $Q = q.A = (116008)(\frac{\pi(0.020)^2}{4}) = 36.4$ W

Therefore due to the amount of energy that is required to be put through such a small area, which is physically very difficult, this measurement idea was not carried on with. Also there were problems in construction of the probe due to the size and the fact that it had to be sealed against steam at about 160 kPa and 150°C.




7.5
4
4
ϕ 2
ϕ 2
ϕ 2
ϕ 11
Insulation board
12
4
ϕ 15
Insulation Section
Scale : NTS
Date : 22/7/90
Drn : M. Cooper
Drg No. 2


Heating Element
hole for thermistor
4
metal plate stst 316
ϕ 2
2.5
ϕ 11
All Dimensions in mm unless stated
University of Canterbury
Chemical Engineering Dept.
for Canterbury Timber Products Ltd.
Heating Element Plate
Scale : NTS
Date : 22/7/90
Drn : M. Cooper
Drg No. 3

APPENDIX C

The following calculations were performed to check the feasibility of cooling the dryer wall enough to allow condensation to take place so keeping the wall wet and hence reducing the build-up of resinous material. However the calculations show that assuming condensation, as this has a significant affect on heat transfer, the amount of heat that is required to be removed is impractical. If on the other hand no condensation is assumed the amount of heat that is required to be removed is reasonable, but there are other associated problems as outlined in the discussion (P 35).

Calculation :

For condensation to occur the temperature of the wall must be less than the air dew point. Assume that the wall area of concern is half way along the dryer and at this point the dryer air temperature and humidity has dropped 3/4 of the difference between the inlet and outlet temperatures.

Typical conditions :

Ambient conditions : 15^{o}C and 65% relative humidity
Inlet Temp : 200^{o}C
Outlet Temp : dry bulb 64.3^{o}C
wet bulb 61.0^{o}C
hence outlet air has 0.10 kg H_2O/kg air
and water from ambient air is 0.007 kg H_2O/kg air
hence water taken up in dryer = 0.10 - 0.007 = 0.093 kg H_2O/kg air
and at cooling panel 3/4 of water has been taken up by the air
: = 0.06975 kg H_2O/kg air
and temperature (dry bulb) of air is 98^{o}C
therefore at these conditions the dew point is 51.1^{o}C
hence the wall temperature needs to be this or below for condensation to occur.
Hence the following calculations were performed :

CTP DRYER HEAT CALCULATIONS

(assuming no condensation - only forced convection)

Ti (C) =	98
To (C) =	10
Wall Thickness L1 (m) =	0.003
Insulate Thickness L2 (m) =	0.03
Wall K1 (W/m.K) =	42.9
Insulate K2 (W/m.K) =	0.0389
Hh (W/m^2.K) (estimated) =	100
Hc (W/m^2.K) (estimated) =	10
Area (m^2) =	1
1/Hh.A =	0.01
L1/K1.A =	6.993E-05
L2/K2.A =	0.7712
1/Hc.A =	0.1
Th - Tc =	88
Q (with insulation)(W/m^2) =	99.85
Q (without insulation)(W/m^2) =	799.49
With Insulation	
Temperature of inside wall (C)=	97.00
Temperature of outside wall (C)=	19.99
Without Insulation	
Temperature of inside wall (C)=	90.01
Temperature of outside wall (C)=	89.95
T condensing inside wall(C)=	50
Q required (W/m^2) =	4800
With Water Cooling	
Hw (W/m^2.K) (estimated) =	1000
1/Hw.A =	0.001
Temp of inlet water (C) =	10
Cp of Water @ 300K (J/kg.K) =	4183
Temp of outlet water (C) =	40
Mass Flow of Water (kg/s) =	0.0383
Mass Flow of Water (l/min) =	2.30

CTP DRYER HEAT CALCULATIONS

(assuming condensation)

Ti (C) =	98
To (C) =	10
Wall Thickness L1 (m) =	0.003
Insulate Thickness L2 (m) =	0.03
Wall K1 (W/m.K) =	42.9
Insulate K2 (W/m.K) =	0.0389
Hh (W/m^2.K) (estimated) =	10000
Hc (W/m^2.K) (estimated) =	10
Area (m^2) =	1
1/Hh.A =	0.0001
L1/K1.A =	6.993E-05
L2/K2.A =	0.7712
1/Hc.A =	0.1
Th - Tc =	88
Q (with insulation)(W/m^2) =	100.99
Q (without insulation)(W/m^2) =	878.51
With Insulation	
Temperature of inside wall (C)=	97.99
Temperature of outside wall (C)=	20.10
Without Insulation	
Temperature of inside wall (C)=	97.91
Temperature of outside wall (C)=	97.85
T condensing inside wall(C)=	50
Q required (W/m^2) =	480000
With Water Cooling	
Hw (W/m^2.K) (estimated) =	1000
1/Hw.A =	0.001
Temp of inlet water (C) =	10
Cp of Water @ 300K (J/kg.K) =	4183
Temp of outlet water (C) =	40
Mass Flow of Water (kg/s) =	3.8250
Mass Flow of Water (l/min) =	229.50

APPENDIX D

These are some examples of numerous photographs taken. All photographs were taken at 125th of a second shutter speed and an 'f' stop of 2.8.

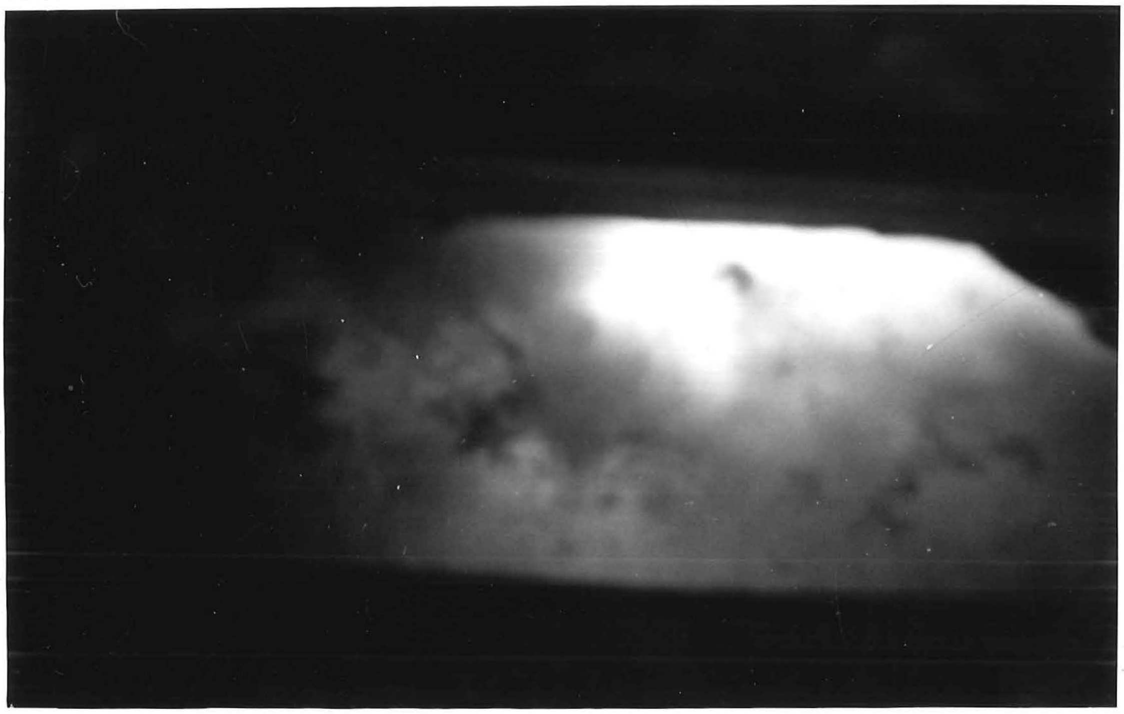


Photo D-1 taken 8/11/90 with a focal length of 280 mm (11")

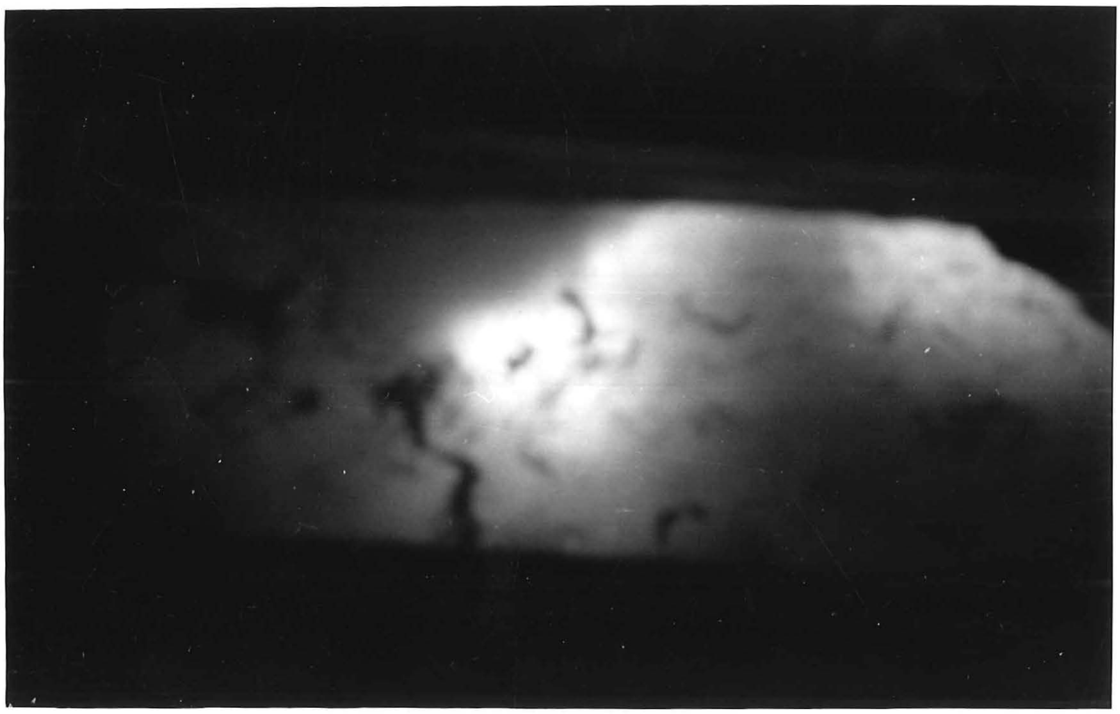


Photo D-2 taken 8/11/90 with a focal length of 280 mm (11")

Flow right to left and bottom of photo is inside of bend, photos were taken from below looking up.

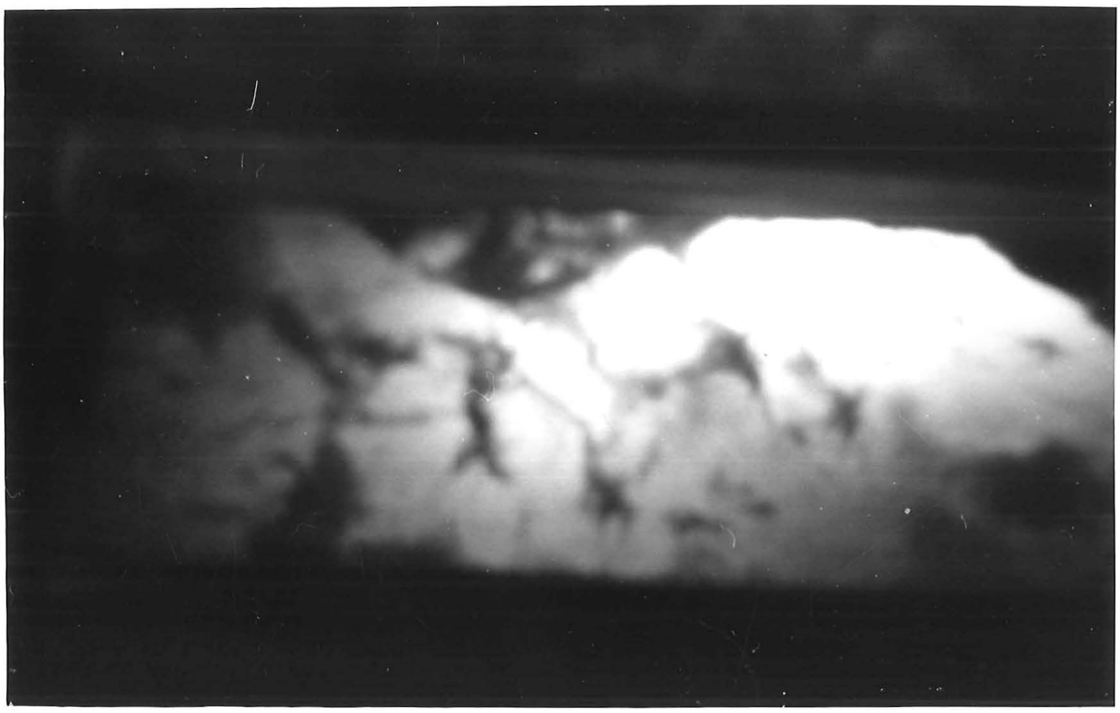


Photo D-3 taken 8/11/90 with a focal length of 280 mm (11")

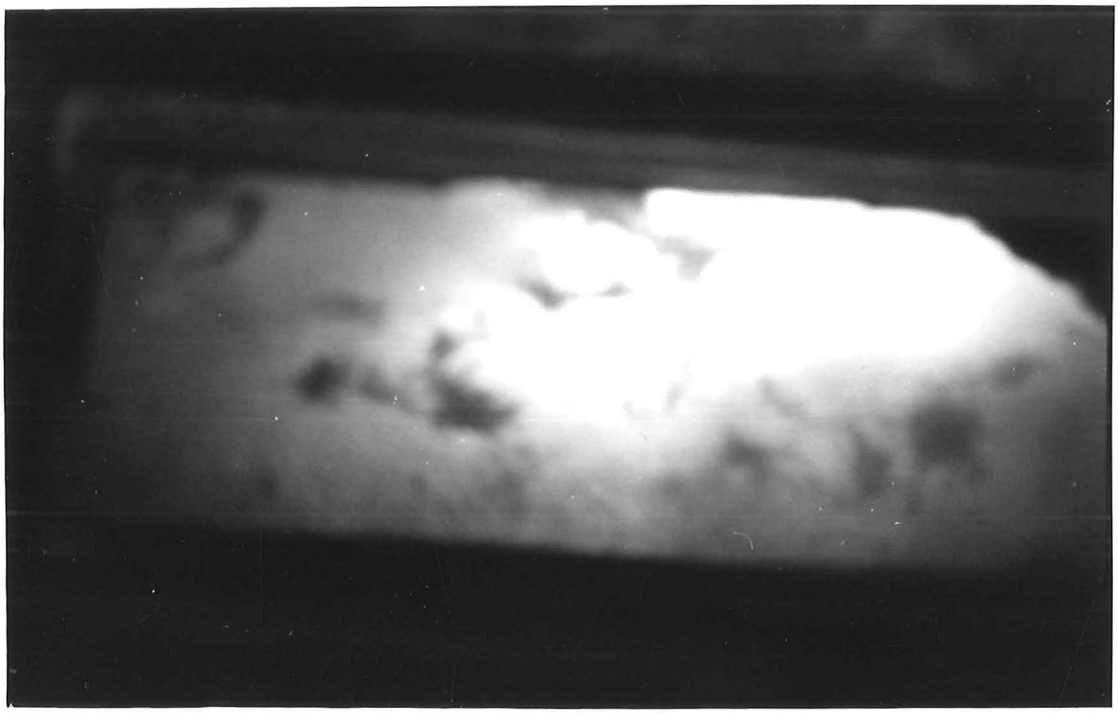


Photo D-4 taken 8/11/90 with a focal length of 280 mm (11")

Flow right to left and bottom of photo is inside of bend, photos were taken from below looking up.

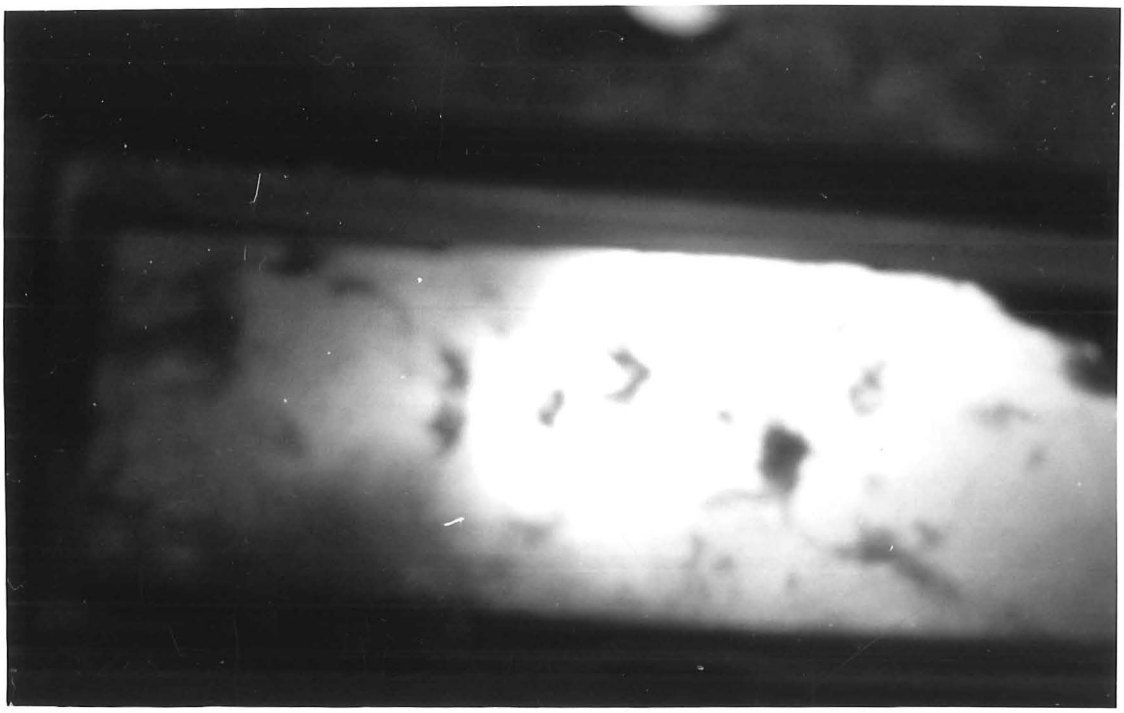


Photo D-5 taken 8/11/90 with a focal length of 280 mm (11")

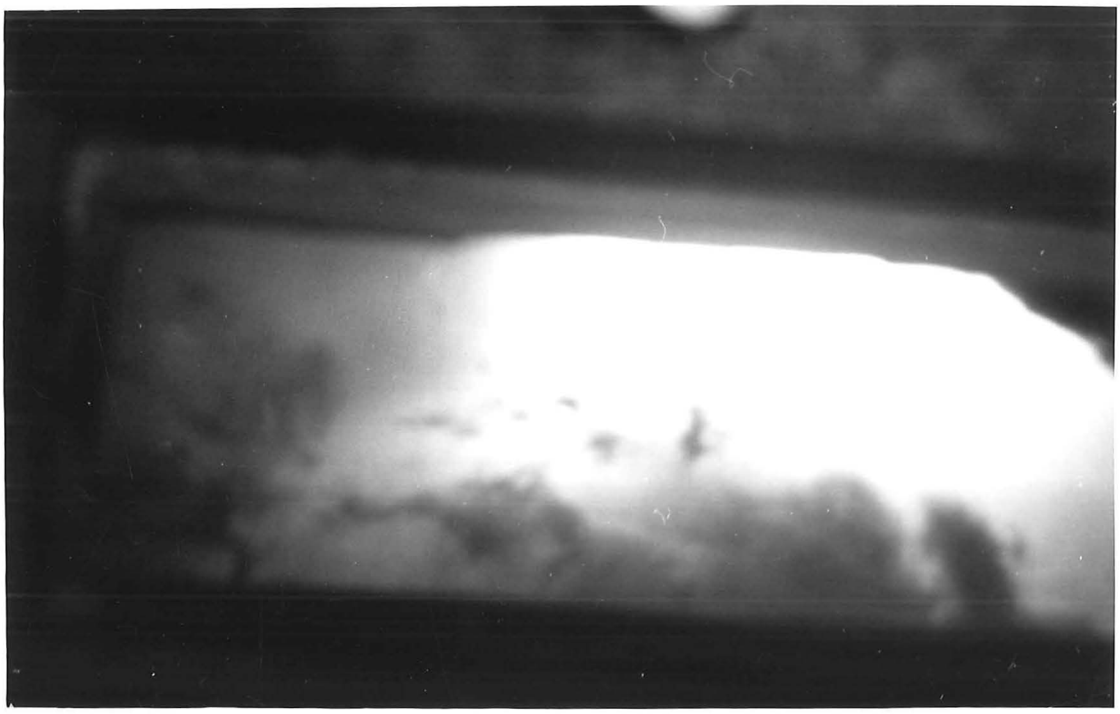


Photo D-6 taken 8/11/90 with a focal length of 280 mm (11")

Flow right to left and bottom of photo is inside of bend, photos were taken from below looking up.

Note the resin jet clearly visible in these next two photographs.

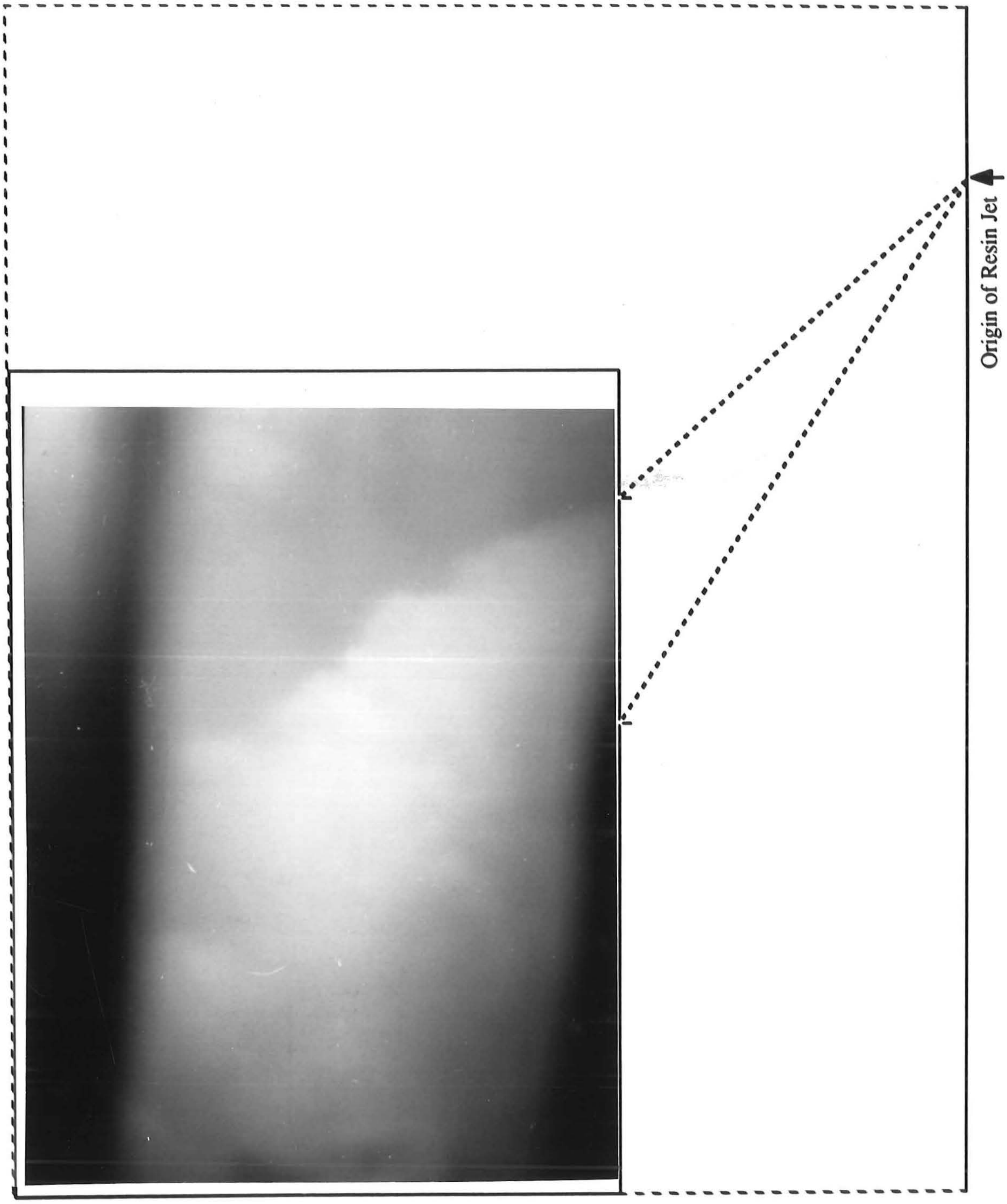


Photo D-7 taken 7/12/90 with a focal length of 305 mm (12")
Resin flow 35 litres/minute

Flow right to left and bottom of photo is inside of bend, photos were taken from below looking up.

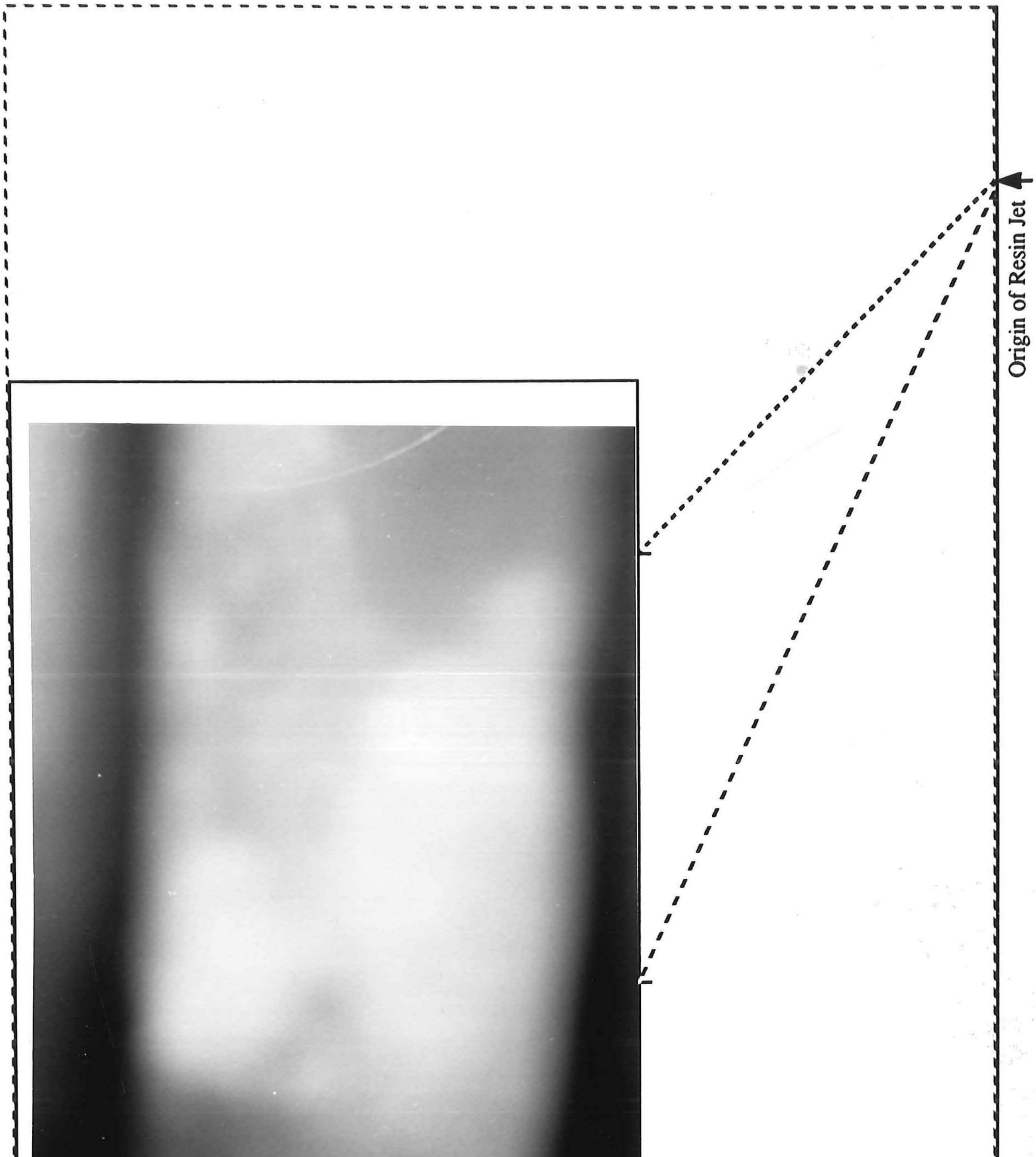


Photo D-8 taken 16/1/91 with a focal length of 305 mm (12")
Resin flow 23 litres/minute

Flow right to left and bottom of photo is inside of bend, photos were taken from below looking up.

These next two photos appear different as the focal distance was completely different to the rest of the photos and the fibre closest to the camera was focused on.

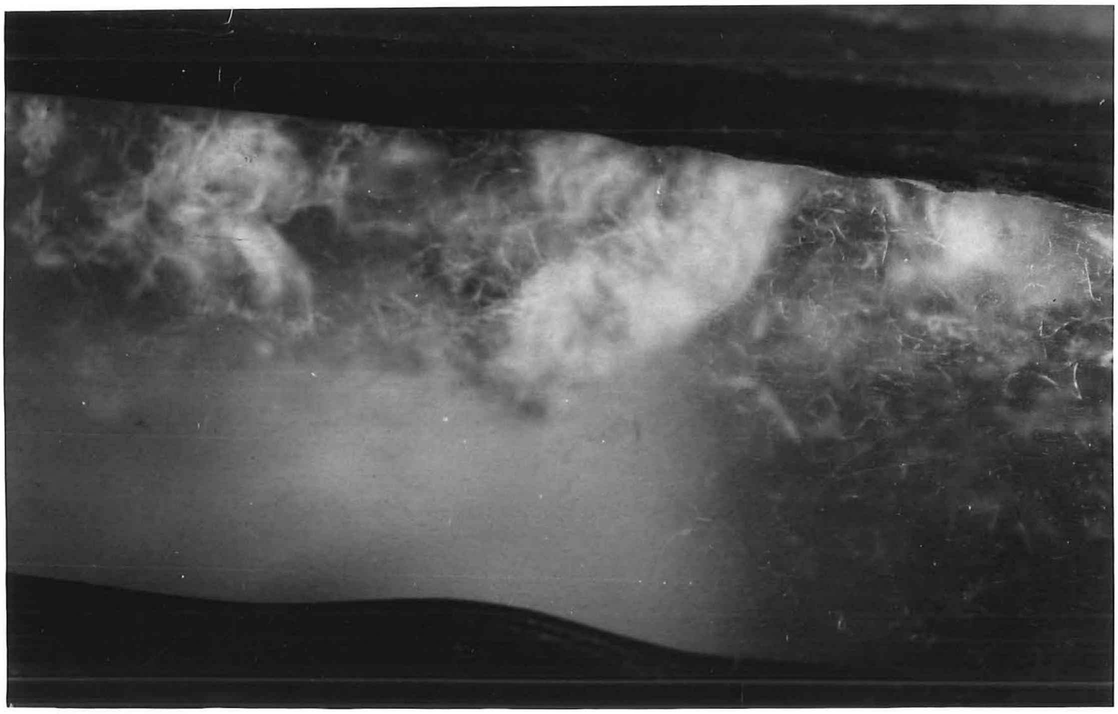


Photo D-9 taken 6/3/91 with a focal length of 250 mm (9.86")

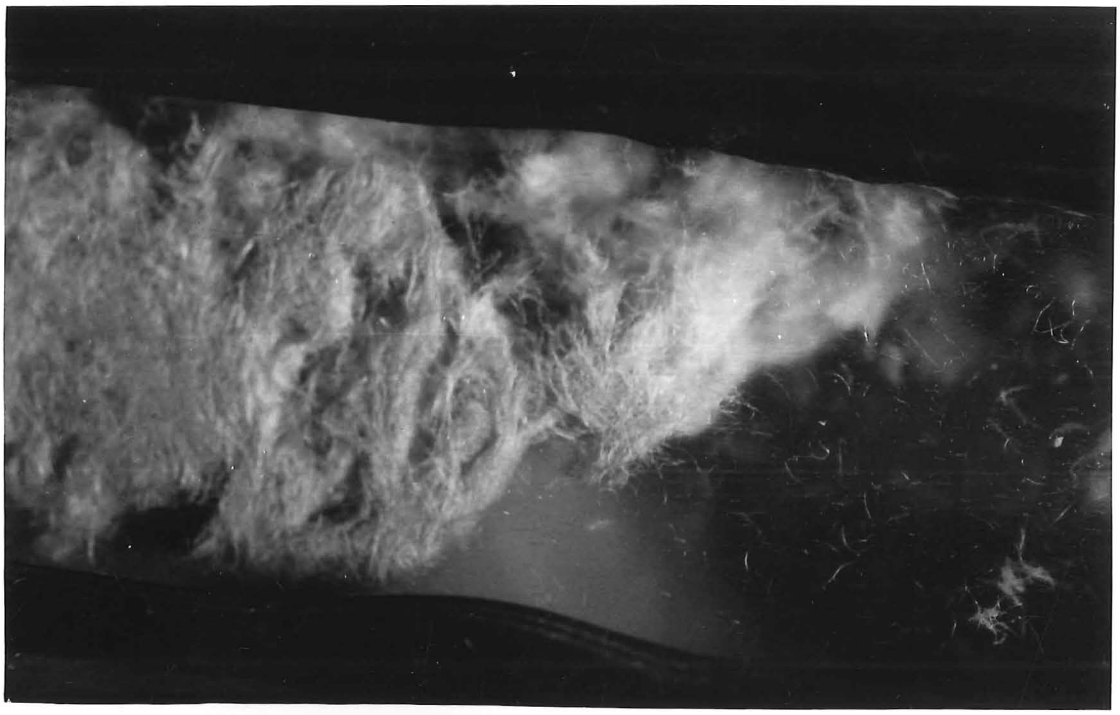


Photo D-10 taken 6/3/91 with a focal length of 250 mm (9.86")

Flow right to left and bottom of photo is inside of bend, photos were taken from below looking up.